Flowness + FlowBlocks

Uncovering the Dynamics of Everyday Life through Playful Modeling

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Submitted to the Program in Media Arts & Sciences,
School of Architecture & Planning
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Abstract

It is not easy to understand the dynamics underlying everyday life. The change around us is so ubiquitous; the processes governing change are invisible; the relationships between cause & effect are usually disconnected in time or space, and probabilistic causation adds uncertainty to the mix.

This dissertation is about a new modeling language and a tangible simulation environment that together help children gain an intuitive understanding of the dynamics underlying everyday life phenomena, from fashion trends and financial markets fluctuations to vicious cycles of violence and virtuous cycles of popularity growth.

I present the Flowness modeling language, a unique combination of Systems Thinking languages that results in an intuitive-to-understand yet computationally simulate-able language. I present FlowBlocks: a tangible learning technology designed in the spirit of early childhood construction kits (a field pioneered by Friedrich Froebel), with special attention to physical representation of abstract concepts (a field pioneered by Maria Montessori). FlowBlocks are a set of wooden blocks with embedded computation that simulate continuous flow using a moving light signal, making dynamic processes visible and manipulable.

I provide evidence that playful modeling using FlowBlocks is not only engaging for children but indeed helps them pay attention to the underlying causality of everyday life situations. Moreover, I show that a FlowBlocks workshop helps middle-school aged students understand core Systems Thinking concepts such as Inflows, Stocks, Outflows, Positive Feedback, and Negative Feedback - by generating their own analogies using FlowBlocks as an interactive model.

I conclude that Flowness + FlowBlocks can serve as an effective learning aid to introduce children to Systems Thinking concepts in a collaborative playful modeling process, and develop children's intuitive understanding of the dynamics underlying everyday life situations.

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CHAPTER 1. INTRODUCTION

The world around us is not in stillness, but rather in "Flowness". Everything around us is interconnected and constantly changing, even if our senses cannot detect the change or the connection. The water in a peaceful lake, rocks and mountains, the cells that make our hands; are all in a state of continuous flow. It is not easy to understand these dynamics. Researchers have shown that people have poor understanding of the interconnected, dynamic world around them (Booth-Sweeney & Sterman, 2000; Dorner, 1989; Resnick, 1994; Sterman, 1994).

This dissertation is about a new modeling language and a tangible simulation environment that together help children gain an intuitive understanding of the dynamics underlying everyday life situations. From depression cycles to fashion trends, from financial markets fluctuations to addictive behavior, from vicious cycles of violence to the challenges of dieting - interconnected feedback loops of matter & information are the mechanism underlying the constant change we experience in our everyday lives.

Norbert Weiner uncovered the mathematical foundation for feedback behavior in his seminal cybernetics research (Wiener 1948, 1954). The language he used (differential equations) is very powerful, but unfortunately is not accessible to children or novices. Jay Forrester and his MIT Systems Dynamics group created two languages that are more accessible: the Stocks & Flows modeling language and the Causal Loops Diagrams language (Forrester 1961, Senge 1990). Stocks & Flows is a visual modeling language and therefore more accessible than differential equations, but is still too complicated for children or novices. The Causal Loops Diagrams language is a brilliant diagramming convention that is accessible to novices, but is not computationally simulate-able.

I this dissertation I present Flowness, a modeling language that is both accessible to novices and computationally simulate-able. I define the Flowness Universal Models, a set of common dynamic patterns that uncover the casual models underlying the dynamics of everyday life situations.

I also present FlowBlocks, a tangible implementation of the Flowness modeling language, implemented as a "computational construction kit" with special focus on "conceptual manipulation". FlowBlocks are a set of wooden blocks with embedded computation that simulate continuous flow using a moving light signal. FlowBlocks elements snap together using magnets to form many different configurations, making it easy to build and simulate the Flowness Universal Models.

The unique design of FlowBlocks has been inspired by the great Learning Objects designers of the 19th and 20th centuries: Friedrich Froebel & Maria Montessori. In an effort to inform and inspire contemporary designers of interactive learning technologies, I uncover the design principles of Froebel & Montessori and trace their historical influences, showing how each of them belongs to a different school of thought. I continue and present a new classification I developed for educational toys and Learning Objects: the "Conceptual Manipulation" vs. "Construction & Design" classification.

To evaluate the effectiveness of FlowBlocks as a learning aid, I defined three research questions and conducted relevant evaluations.

Question 1:

> Can FlowBlocks serve as an educational scaffold for children, helping them progress from structure-level to behavior-level reasoning in the context of Systems Thinking?
>
> We conducted a series of 50 minute FlowBlocks play sessions with six pairs of 4th and 5th grade students. We transcribed the sessions' video recordings, scored the children's phrases to track their progress from structure-focused terminology to behavior-focused terminology, and analyzed the results. Our findings show that with the educational scaffolding built into the blocks' design, the students were able to move beyond the structural level and focus on behavioral aspects of the causality within the system.

Question 2:

When children use FlowBlocks to explore models & simulations of dynamic systems, what are the different trajectories they move through while they transition from focusing on a simulation's surface features to focusing on the deeper underlying behavior?

I facilitated a collaborative workshop with eleven 8^{th} – 10^{th} grade students who had no prior instruction in Systems concepts. I asked the participants to write in their journals "what they think the blocks are about, what they are good for" at three different times during the workshop's first sessions. I color-coded their answers, identifying different levels of structure-focused and behavior-focused terminology. I organized the color-coded clusters in a table to reflect the change over time, and a clear trajectory became apparent. My analysis clearly shows the progress participants had throughout the first two hours of the workshop, and makes the trajectory visible, both on the individual and group level.

Question 3:

Can a FlowBlocks collaborative workshop help students gain a better understanding of Systems Thinking concepts?

I documented and analyzed the workshop participants' daily-life analogies in eight analogy-making activities. I classified the examples as correct or incorrect, and for each incorrect one I concluded which misconception is involved. My analysis shows a clear improvement in the number of correct analogies for models that involve Inflow, Stock, Outflow, Positive Feedback, and Negative Feedback.

Overall, my findings show that FlowBlocks can serve as an effective learning aid to introduce middle-school aged children to Systems Thinking concepts in a hands-on collaborative process of playful modeling.

CHAPTER 2. EXTENDED EXAMPLE

Fernando, a 14 year-old boy, is starting to play with a limited set of blue and light-blue FlowBlocks. He does not understand yet what they are about, but he is intrigued by the look & feel of the wooden blocks with the translucent arrow-shaped symbols. He explores the blocks with both hands, and the magnetic connectors lead him to attach the blocks to one another in the correct way.

To his surprise, the arrow-shaped symbols flash for an instant with bright red light. He clicks the red button on one of the blocks, and a light is sent out from that block to the next one, creating a sequence of lights that makes the blocks blink one after the other, creating an illusion of a "light entity" passing from block to block. He clicks the button again, and watches the generated light sequence. He spends the next few minutes clicking as fast as he can, generating more light sequences.

Now he connects more blocks to his configuration, creating a longer "train track" for his light sequence. Soon enough he runs out of blocks, he wants to create a longer path. He looks around at his classmates, all of them playing with FlowBlocks as well. Maria, who seats to his left, reached the same situation as he did. They look at each other and decide to join forces and have twice as many blocks. They create longer chains together, and this time use two buttons to generate more than one light sequence at a time.

Their classmates see what they created, and many small groups are naturally formed. At this point, the workshop facilitator walks around and hands them another block, an orange one, with a numeric display module attached to it.

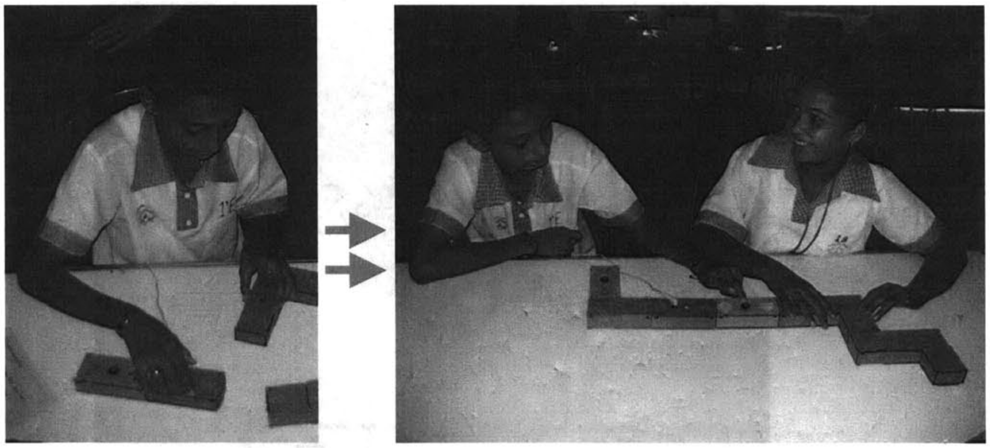


Figure 1: natural progress from individual modeling to collaborative modeling

Maria and Fernando connect the new orange block to their configuration, and send a light sequence towards it. As they watch it they hear someone saying: "ah, I get it, it's counting the lights!" For every click on the button the light starts passing from block to block until it reaches the orange block where it is being aggregated. They experiment, changing the location of the orange counter within their chains, sending two lights at once into it, clicking the button as fast as they can to increase the numbers faster and faster until they reach the limit of the 3-digit capacity.

As they are busy experimenting with the orange block, the workshop facilitator hands them another light-blue block. This one is similar to the one with the button, but instead of the button it has a dial mounted on it, like a volume dial in a home stereo system. They connect it to their configuration instead of the button block, and turn on the dial. A stream of lights is sent out, like a flow of light. The more they turn the dial, the faster the light flow is.

Figure 2: experimenting with continuous flow and dynamic accumulation

They look at the orange counter and see how quickly the numbers accumulate. They turn off the dial just a little, and see how the numbers still accumulate, but at a slower rate. "Hey what is this dial for?" asks Maria as she points to a dial mounted on the orange block, towards its output connection. "It looks just like this new one that generates the flow of light", says Fernando. Maria turns it on just a little bit, trying to understand its purpose.

As she turns the dial, the numbers on the orange counter start to decrease. The more she turns the dial, the faster the numbers decrease. "ah, I get it, it's making the light go out from the orange block, like a park with people coming into the park and other people leaving the park!"

Fernando quickly connects a few blocks after the orange one, and now they see how the lights continue to flow past the orange counter, just as if the orange block generates light sequences. "What do you think will happen when there's nothing left in the orange counter?" asks Fernando.

Figure 3: simulating a dynamic "people-in-the-park" system with people coming and leaving

They watch anxiously as the numbers in the orange counter decrease, when it reaches zero, the light sequence stops, and the counter is stable at zero. "Cool" says Maria, "now let's try to send light in and out of the orange counter at the same time, like a stream of water making a little pond and then flowing away!" "How about trying to loop it so the light going out from the orange counter will go back into it?" suggests Fernando.

Their classmates hear their excitements and come to watch, and quickly learn how to use the orange block's outflow dial in their own configurations.

This scenario presents only a small part of the models children can construct using FlowBlocks. As the workshop progresses, children model more complicated situations including: direct cause & effect (short term consequences), delayed cause & effect (long term consequences), closed and open systems (conservation of matter vs. "cradle-to-grave" systems), reinforcing growth due to positive feedback loops (exponential growth), balanced growth due to negative feedback loops (goal-based growth), probabilistic causality, dynamic equilibrium, oscillation, and more.

CHAPTER 3. BACKGROUND AND RELATED WORKS

In this chapter I present the two theoretical frameworks essential to my work. Theoretical framework 1 is ***Systems Thinking Languages***, and theoretical framework 2 is ***Tangibility & Learning***. In addition, I present an overview of ***Related Works*** from the research community.

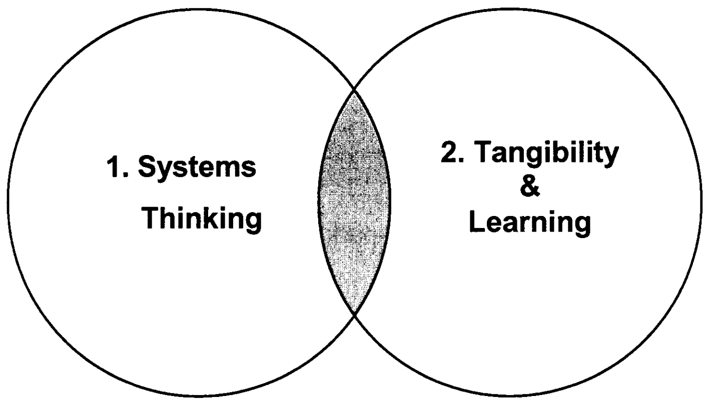


Figure 3: The theoretical frameworks that underlie my research

Theoretical Framework 1: Systems Thinking Languages

During the 20^{th} century we experienced major advancements in the way scientists understand dynamic behavior in natural and social systems. Different mathematical frameworks and modeling techniques have been developed to better understand feedback behavior and the mechanism underlying constant change. The core concepts of systems were mathematically defined such as positive and negative feedback, stocks and flows, and time delays (Wiener 1948, Forrester 1961). Researchers have mapped the "Generic Structures" commonly observed in natural and social systems, dynamic structures that generate behaviors such as exponential growth and decay, goal seeking, oscillation or self-regulation (Forrester 1961, Senge 1990, Richmond 1992, Sterman 2000).

Differential equations: Weiner and his followers used differential equations as the modeling language. This language is very useful for engineers and scientists, but is not helpful for non-technical people. Over the years, the engineering and scientific communities gained a great understanding of feedback systems and their role in natural and social systems. However, the general population could not share the same level of understanding, and the mathematical-based languages stayed within the domain of the scientists.

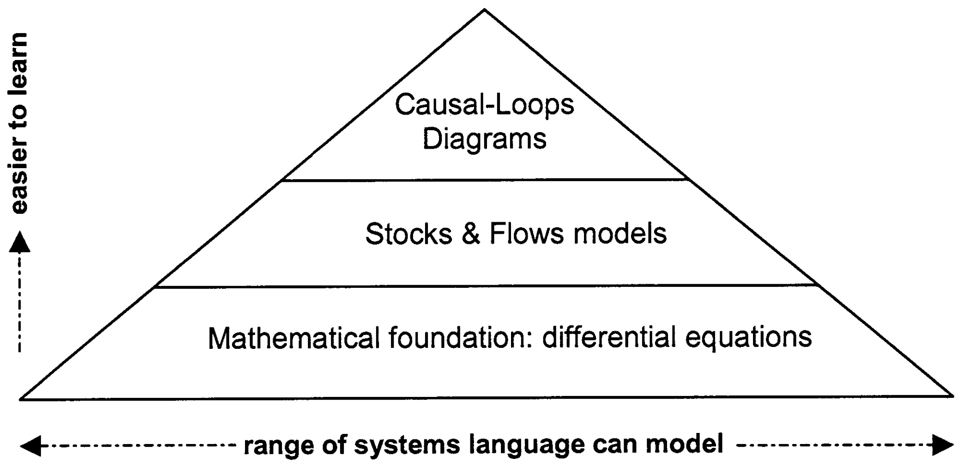


Figure 4: Tradeoffs between the different Systems thinking languages

Stocks & Flows: Forrester, a trained engineer with a hands-on experience designing feedback-based control systems, came to the conclusion that the biggest impediment to progress comes not from the engineering side of industrial problems, but from the management side. This is because, he reasoned, social systems are much harder to understand and control than are physical systems. Forrester formed the System Dynamics group at MIT's Sloan School of Management and used the stock-flow-feedback language, based on hand-calculations of differential equations, to understand social systems. During the late 1950s and early 1960s, they created the first computer modeling tools. Richard Bennett created the first system dynamics computer modeling language called SIMPLE (Simulation of Industrial Management Problems with Lots of Equations) in the spring of 1958. In 1959, Phyllis Fox and Alexander Pugh wrote the first version of DYNAMO (DYNAmic MOdels), an improved version of SIMPLE. The DYNAMO tool was effective in simulating models, but was text based and equation-based and therefore still not accessible to novices.

In 1987, Barry Richmond, who studies System Dynamics in Forrester's group, created a user-friendly software-tool with a visual modeling language called STELLA. The STELLA modeling and simulation tool enabled mangers, consultants, and event teacher to create

Stocks & Flows models and simulate them within the STELLA environment. To create a new model using STELLA one had to write math equations. The math equations involved simple operations such as addition, multiplication or division. Although the required math level in STELLA is very low, and a great improvement compared to DYNAMO or the original differential equations, the nature of the interface design and the math required to create a relationship between a model's entities was still a barrier for learning with regards to novices.

1991, Bob Eberlein, who also studied System Dynamics in Forrester's group, formed Ventana Systems Inc. who developed Vensim, a Stocks & Flows modeling and simulation tools. Vensim is different from STELLA in many ways, but the core stocks & flows modeling language is similar, and the use of math operations as the main way to set relationships between entities is still maintaining the barrier for learning with regards to novices.

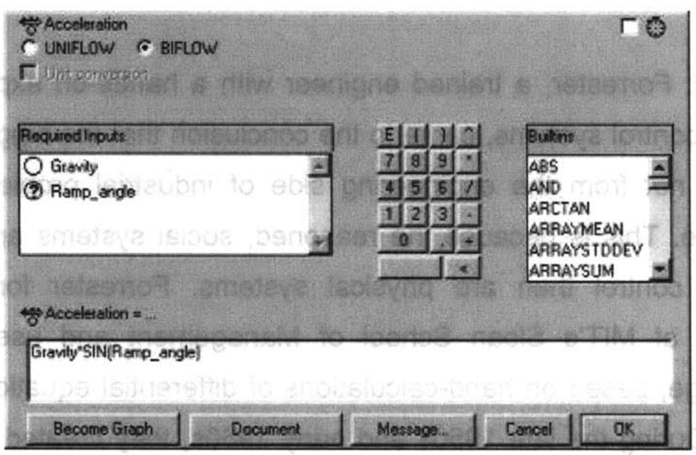


Figure 5: setting a relationship between a flow and a stock in STELLA

Causal Loops Diagrams: A common tool used by systems thinking practitioners and educators, Causal Loops Diagrams (CLDs) is a language that describes the relationship between the different entities in a system. CLDs aids in visualizing how interrelated variables affect one another. The diagram consists of a set of nodes representing the variables connected together. The relationships between these variables, represented by arrows, can be labeled as positive or negative. A positive label sets a "more is more" relationship, in which an increase in one variable will lead to an increase in the other variable, or a decrease in one variable will lead to a decrease in the other variable. A negative label sets a "more is less" relationship, in which an increase in one variable will lead to a decrease in the other variable, or a decrease in one variable will lead to an increase in the other variable.

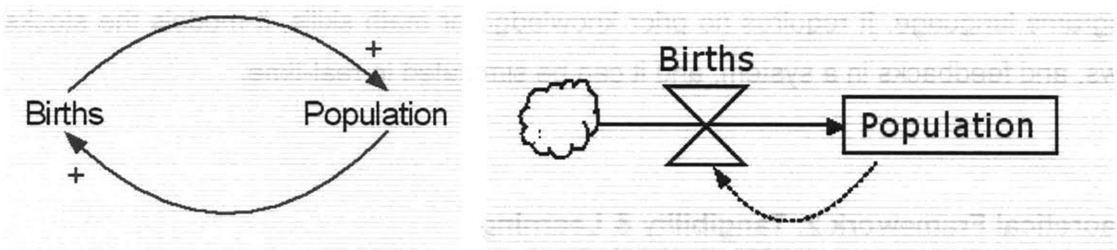


Figure 6.a: A simplified "population growth" model using the CLD language (left) and the Stocks & Flows language (right)

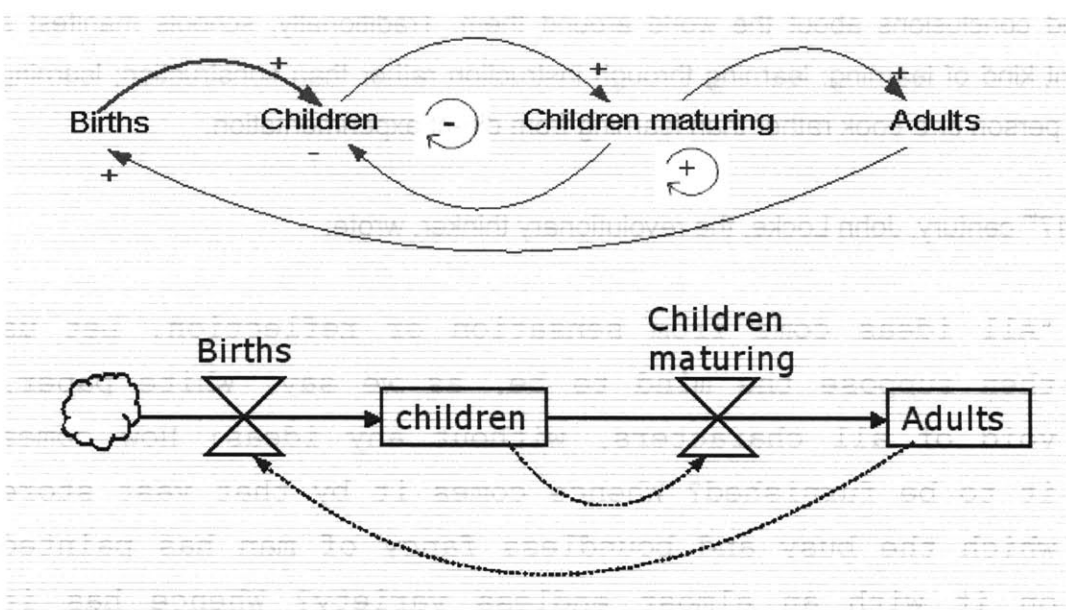


Figure 6.b: A simplified "population maturing" model using the CLD language (top) and the Stocks & Flows language (bottom)

The language of Causal Loops Diagrams is a simple yet powerful language. It does not involve any prior knowledge in mathematics and it captures the essence of constant change – feedback loops. On the other hand, CLDs have a major disadvantage over Stocks & Flows – they cannot be computationally simulated. As a result, people need to imagine what the unfolding system behavior will look like, and for many people this might be a barrier for learning. Certainly in a group situation, it is hard to know if all group members imagine the same system behavior, and therefore the group cannot ground a discussion on a common starting point.

The language I have created is a mix of the Stocks & Flows and the Casual Loops Diagrams language. It requires no prior knowledge or math skills, it models the stocks, flows, and feedbacks in a system, and it can be simulated in real-time.

Theoretical Framework 2: Tangibility & Learning

Throughout human history, people learned by interacting with their physical environment. Children played with rocks and sticks, water and sand, experimented and reached conclusions about the world around them. Traditionally, schools manifest a different kind of learning: learning through instruction rather than construction; learning from a person or a book rather than learning from direct experimentation.

In the 17th century, John Locke, the revolutionary thinker, wrote:

> "All ideas come from sensation or reflection. Let us then suppose the mind to be, as we say, white paper, void of all characters, without any ideas: How comes it to be furnished? Whence comes it by that vast store which the busy and boundless fancy of man has painted on it with an almost endless variety? Whence has it all the materials of reason and knowledge? To this I answer, in one word, from experience."
>
> (Locke, An Essay Concerning Human Understanding, 1698)

In this section of thesis I review the long tradition of research and practice concerning the learning potential situated in physical interaction with tangible objects. I will start my review with the philosophers, epistemologists, and educational practitioners that are the forefathers of the field: Locke, Rousseau, Itard, Pestalozzi, Froebel, Montessori, Piaget, and Dewey. I will utilize this review to present a new classification for manipulatives: sets of physical objects consciously designed as learning environments. I will continue with a review of the Digital Manipulatives field, and will highlight related works. In addition, I will provide a survey of Tangible User Interfaces (TUI) frameworks, and report on key research findings in the TUI field that are relevant for learning.

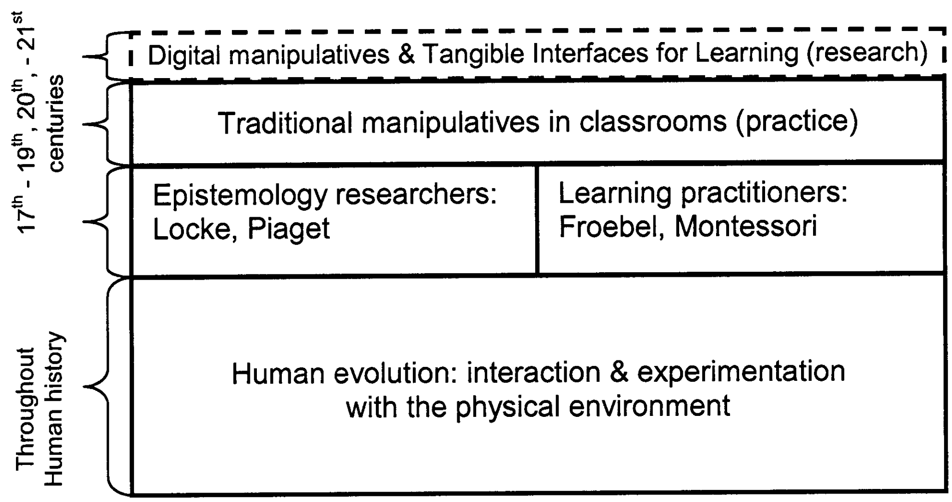


Figure 7: the history & reasoning behind tangibility & learning

John Locke: "knowledge comes from experience"

In the 1690s, John Locke, a key contributor to the Empiricism movement in philosophy, wrote 'An Essay Concerning Human Understanding'. In the essay, Locke laid the foundations for the 'learning from experience' movement, the ancestor of today's 'learning by doing' school of thought. In 17th century's terminology, "experience" meant "experiment" (BBC radio archive, 2004). Hence, learning from experience, from sensation and reflection, is learning from hands-on experimentation and reflection. Locke also suggested a design for a Learning Object: "There may be dice and play-things, with the letters on them, to teach children the alphabet by playing; and twenty other ways may be found, suitable to their particular tempers, to make this kind of learning a sport to them." (Locke, 1693, P.148).

"For example; what if an ivory-ball were made like that of the Royal-Oak lottery, with thirty-two sides, or one rather of twenty-four or twenty-five sides; and upon several of those sides pasted on an A, upon several others B, on others C, and on others D? I would have you begin with but these four letters, or perhaps only two at first; and when he is perfect in them, then add another; and so on, till each side having one letter, there be on it the whole alphabet." (Locke, 1693, P.150)

Locke's vision influenced many thinkers who extended Locke's revolutionary educational ideas in different directions. Rousseau extended the experiential side, the open-ended interaction with nature and objects, of learning as a gradual process of experimentation. Condillac extended the sensation side, and developed the theory of sensationalism ("all knowledge comes from the senses") (Knight, 1968). Dewey extended Rousseau's ideas, focusing on a child's interaction with the immediate, familiar adult world. In my opinion, these three philosophers represent three distinct movements within the "learning by doing" school of thought: (1) The "Intelligent Hand" movement, led by Condillac, focused on sensorial interaction with objects as the origin of intelligence (2) The "Experimenting Child" movement, led by Rousseau, focused on open-ended exploration, real-world experimentation, and interaction with nature, as the source of knowledge. And (3) The "Simplified reality" movement, lead by Dewey, focused on direct experience with a simplified version of the immediate, familiar adult world.

Figure 8 below traces the key thinkers associated with each of these movements, progressing towards the revolutionary educational works of Friedrich Froebel, Maria Montessori, and John Dewey, who changed the history of early childhood education.

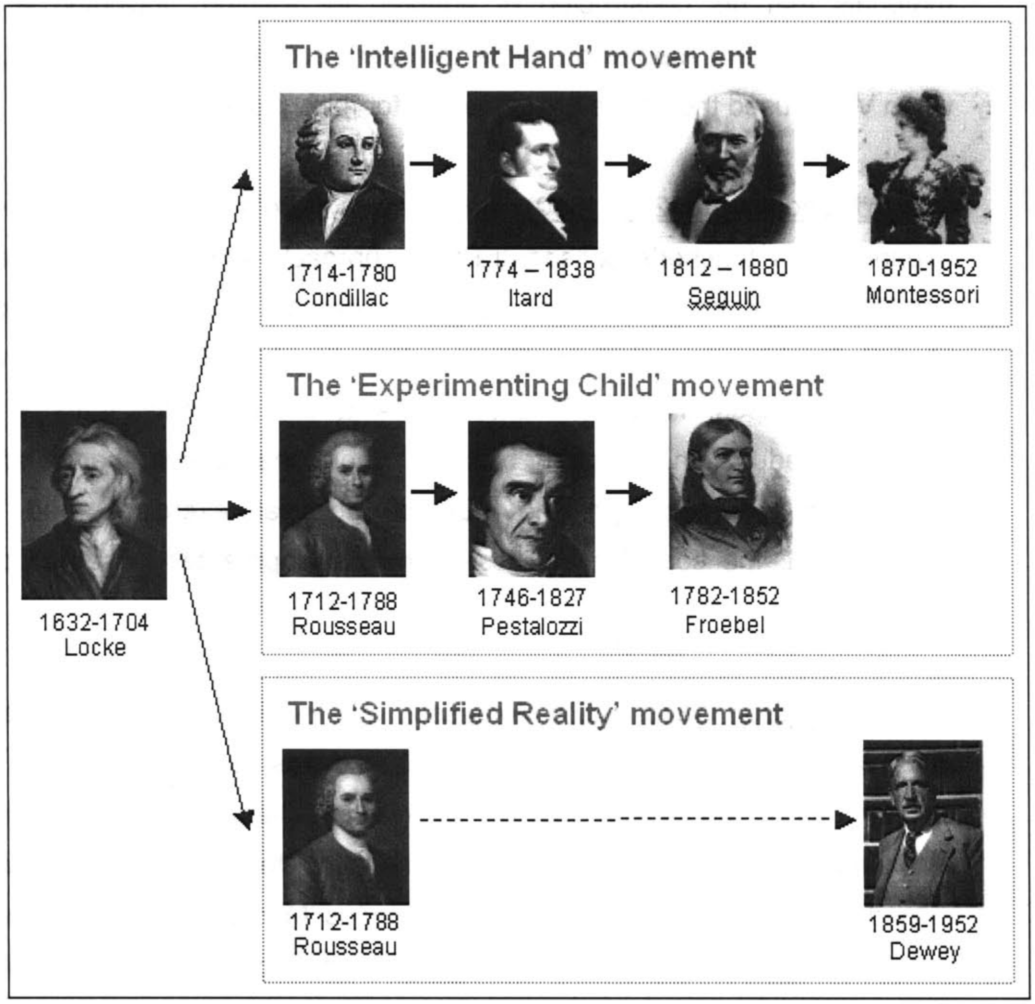


Figure 8: the origins of manipulatives & "learning from experience" school of thought

The 'Intelligent hand' movement

Etienne Condillac (1714-1780): developed the theory of sensationalism (i.e., that all knowledge comes from the senses and that there are no innate ideas). He tried to simplify Locke's theory of knowledge by arguing that all conscious experience is simply the result of passive sensations. (Knight, 1968)

Jean-Marc Gaspard Itard (1774-1838): devised several new methods for educating and treating the deaf and mute. His educational approach relied heavily on sensory-training and stimulation (Itard, 1962). He became famous while insisting on treating Victor, 'The Wild Boy of Aveyron', the boy that was found in the woods near the village of Lacaune, France in 1797. Itard worked closely with Victor, trying to teach him how to speak. Itard used common materials that he ‘constructed or adapted for training’, including a physical alphabet set. Itard reports on some transitory success of his methods, notably when Victor used the letters L A I T to ask for milk. (Lane, 1976)

Edward Seguin (1812 – 1880): Seguin was Itard’s pupil. He improved and expanded his teacher's sensory-training approach, and put it into practice in special schools for retarded students. He earned fame both in Europe and abroad for his nonverbal intelligence test (Itard, 1962), a board with ten geometric shapes. Today, the shapes boards are a popular material in early childhood education. Seguin believed that ‘the active hand stimulated intelligence’, that through the use of physical exercises and sensory development, the cognitive abilities of the developmentally disabled could be increased.

Maria Montessori (1870-1952): Montessori was the first woman in Italy to earn a physician degree. She was Seguin’s pupil, and was passionate to help retarded children learn. Montessori studied Seguin and Itard’s work intensively, and extended their sensory training and stimulation techniques. Specifically, she extended their training materials into her famous ‘Montessori materials’, what she called the ‘didactic materials’. In a program she developed for children with difficulties in reading and writing, she emphasized learning through repeating exercises “Looking becomes reading; touching becomes writing”. Montessori was extremely prolific, and created an educational philosophy & practice (the Montessori method, 1916), extending her work with retarded children to normal children through her network of ‘casa de bambini’. With regards to the Learning Objects she designed (the famous ‘Montessori materials’), she started with Itard’s and Seguin’s materials (such as Itard’s alphabet letters and Seguin’s shapes/forms board), and extended them into brilliant designs in four main categories: Cultural, Language, Mathematics, and Sensorial. Cultural included animals and world puzzles; Language included alphabets, word kits, and grammar kits; Mathematics included number rods, number figures, fraction circles, multiplication boards etc.; Sensorial included wooden towers, stairs, cylinders, color tablets, sound cylinders, touch fabrics and more.

Montessori's method had several educational principles. I will focus on the ones related to the design of Learning Objects, mainly the principles for the 'prepared environment', which involved the teaching materials and the role of the teacher (Montessori, 1949). Montessori wrote that the teaching materials should be designed with the following principles in mind: developmentally appropriate, isolation of properties, stimulation of activity, design that is appealing to children, the materials should be self-guiding (facilitate self-directed learning), should support continuity (image of a ladder, the prepared environment should allow children to progress individually, moving from simple objects to more advanced ones in their own pace), and support group interaction (the materials should support mixed age collaboration). The teacher's role in the Montessori method is to allow the child to act independently, to provide opportunities for learning through indirect teaching, and to provide educational input when needed.

An interesting concept in Montessori's writing is 'Polarization of Attention' – the polarity between moment of activity and moments of reflection. In the following example, Montessori describes an observation of a 13-year-old girl who was deeply engaged with the cylinder blocks:

'In the beginning I was watching the little one, without disturbing her, and began to count how often she repeated the exercise, but then, when I saw that she continued with it for a long time I took the little chair where she sat and put the little chair and the little girl on the table; the little one quickly picked up her cylinder-toy, put the wood block on the armrest of the chair, put the cylinder in her lap and continued to work. Then I asked all the kids to sing; they sang, but the girl continued to repeat the exercise, even after the short song was over. I counted 44 repetitions; and when she finally stopped she did that totally unrelated to the distractions from the environment, that could have disturbed her; and the girl looked around herself with content, as if she woke up from a refreshing sleep. My unforgettable impression was a lot like - what I think - you feel when you discover something.' (Montessori 1952)

The "Experimenting Child" movement

Jean-Jacques Rousseau (1712 – 1778): Rousseau was greatly influenced by Locke in many aspects, including Locke's views on learning and the origins of knowledge (Doyle & Smith, 1997). In 1762 Rousseau wrote a novel called Emile (Rousseau, 1762), about a young boy and his tutor. In Emile, Rousseau lays the foundations for child-centered educational theory and beyond. Instead of being taught other people's ideas, Emile is encouraged to draw his own conclusions from his own experience. For example, Emile is encouraged to break a window in order to find that he gets cold if the window is not repaired. Rousseau emphasizes Individualized education - 'Every mind has its own form'. Rousseau continued to discuss the role of the educator, and described it as 'facilitate opportunities for learning'. He claimed that education comes from three masters: (1) education of nature: the inner growth of our organs and faculties. (2) Education of men: the use we learn to make of our growth. (3) education of things: what we gain by our experience of our surroundings.

In addition, as a romanticist, Rousseau stressed wholeness and harmony through solitude with nature. Emile is not allowed to read books, but is encouraged to experience the world first hand. Rousseau makes one exception, and allows Emile to read one book until adulthood, this book is Robinson Crusoe - an expression of the solitary, independent man that Rousseau seeks to form (Doyle & Smith, 1997).

Johann Heinrich Pestalozzi (1746-1827): Pestalozzi was inspired by the Empiricism movement and specifically by Rousseau's Emile, and in 1805 decided to establish a revolutionary school at Yverdon, Switzerland. He argued that children should learn through activity and through concrete things rather than dealing with books and words (Pestalozzi 1894). Pestalozzi believed that children should be free to pursue their own interests and draw their own conclusions from their observations. He placed a special emphasis on spontaneity and self-activity. Children should not be given ready-made answers but should arrive at answers themselves. The aim of his school was to educate the whole child - intellectual education is only part of a wider plan. He looked for balance, and strived to keep three elements in equilibrium: the hands, heart and head.

Pestalozzi developed a method he called Anschauung - direct concrete observation, often inadequately called 'sense perception' or 'object lessons'. Based on his method, children were not allowed to use words until sufficient Anschauung, direct observation, has occurred (Smith 1997). The concept or topic must be observed in a concrete way. Pestalozzi's followers developed various sayings from his method: from the known to the unknown, from the simple to the complex, from the concrete to the abstract. (Kilpatrick 1951)

Friedrich Wilhelm August Froebel (1782 - 1852): Froebel's original concern was the teaching of young children through educational games at home, in the family environment. Froebel sought to encourage the creation of educational environments that involved practical work and the direct use of materials. He believed that through engaging with the world, understanding unfolds (Brosterman 2002).

Froebel, an agriculture student, visited Pestalozzi's school in Yverdon, Switzerland at 1805 (the year the school was founded). This was after Pestalozzi published a book at 1801 named "How Gertrude Teaches Her Children" (Pestalozzi, 1801), emphasizing that children should not be given ready-made answers but should arrive at answers themselves through self-activity. Froebel was inspired by Pestalozzi's educational ideas and formulated the "Kindergarten System" with emphasis on the use of special play materials ("gifts") in carefully defined activities ("occupations"). Froebel laid his educational philosophy in his book "On the Education of Man" (Froebel, 1826). Froebel "gifts" were 20 carefully designed play materials, such as wooden blocks and dots, geometric paperboard pieces, and geometric metal pieces. The "gifts" and related "occupations" helped young children learn about color, form, geometry and physics through design and story telling activity. Froebel did not design the "gifts" to teach certain concepts, but rather to emphasize the "unification" of life and to help children appreciate "forms of life", "forms of knowledge", and "forms of beauty". Froebel emphasized learning about the world by building and constructing models of real things from the world.

The "Simplified Reality" movement

John Dewey (1859 - 1952): Dewey developed a broad educational philosophy. It seems he was influenced by Rousseau's writings, and like Vygotsky (1896-1934), he viewed the formation of the mind as a primarily social process. Dewey's educational philosophy focuses on three main areas: (1) Experience and reflection - a strong connection to Locke's original views. (2) Democracy and community, and (3) environments for learning (Dewey 1938). The latter is the most relevant to the focus of this paper.

Dewey argues that learning environments should be a simplification of present life: 'I believe that the school must represent present life-life as real and vital to the child as that which he carries on in the home, in the neighborhood, or on the playground' (Dewey 1897, Article II). Children should engage in social activities, learning by doing, specifically by doing activities that are part of real life, the adult's life, the life at home. An interesting example is the laboratory school Dewey and his wife Alice ran at the University of Chicago. In this school, children learned early chemistry, physics, and biology by experimenting with the natural processes involved in cooking breakfast.

A New Classification for Tangible Learning Objects

There are many common themes in the educational philosophies of Montessori, Froebel, and Dewey. They all believe in learning from experience, active learning, by interacting with learning materials and with people. They all believe that controlling the learning environment is the best way to encourage learning, and that teachers should provide opportunities for learning, rather than deliver information and facts directly to learners. In particular, Froebel and Montessori share many design principles in the objects they created. They both design developmentally appropriate objects, highly modular, from materials that promote sensory interaction, with a simple aesthetic design.

But there are also clear differences between them, clear enough to separate their designs to distinct classes.

Froebel's class: Construction & Design

Froebel's artifacts are construction kits, building materials, that promote activities that involve design and model building. His artifacts help children understand the physical world by making models of physical things, his artifacts engage children in an expressive activity, letting them express their own ideas through design and construction. Froebel's artifacts can also be used to learn about geometric relationships, but only as a secondary goal to the design process. For example, Froebel's gifts numbers 3, 4, and 5 are carefully designed building blocks, where the blocks' sizes differ in specific geometric relationships. While children are engaged in a design process, they might also learn about the geometric relationship. Froebel's artifacts are the forefathers of today's building toys category, toys that are design materials, that enable children to build models of physical things, and to express themselves visually using 2D and 3D construction sets. This category include toys like LEGO bricks, Tinkertoys, K'nex, and materials like colored shapes, sticks, paper cuts etc.

I term Froebel's class "***Construction & Design***".

Montessori's class: Conceptual Manipulation

Montessori's artifacts, on the other hand, are not design or construction materials. It is possible, but awkward and unnatural to use Montessori materials to create models of physical things in the world. Montessori's artifacts are about abstract concepts, not the physical world. Each of her artifacts carefully designed to represent a single abstract concept. The most dominant design guideline in her works is 'isolation of properties'. She wanted to make sure that when children interact with one of her materials, the hands-on manipulation process will help them 'absorb' the abstract concept through physical interaction alone, independently, with no teachers guidance, and without any real-world analogy (like Froebel's physical analogies: a house, a train, a tree etc.) For example, consider Montessori's 'long stairs' materials, designed help children 'absorb' the concept of 'a number'. The long stairs are large. The smallest one is 10cm long, and the longest one is 100cm long. They are painted red, to make them appealing to children. When a child plays with the long stairs, the design does not encourage her to build towers, castles, or houses using the 'blocks'. Rather, there is a limited number of configurations. When the child is engaged in the interaction, she has the opportunity to enter the special 'polarization of attention' state (as described in the Montessori section above), and through physical interaction with the hands, 'absorb' the abstract concept. Montessori's artifacts are the forefathers of toys that we see today in toy stores, such as shapes puzzles, sorting toys and stacking toys. In addition, many classroom materials seem to belong to the same category, such as Cuisenaire rods, base-ten blocks, and fraction tiles. Historical artifacts from this category would be the Chinese Abacus, a tangible representation of the abstract concepts of addition and subtraction; or the Russian Matriochka, the wooden dolls that stack into one another, a tangible representation of the volume concept.

I term Montessori's class "***Conceptual Manipulation***".

Dewey's class: Reality Role Play

Dewey did not design learning objects, but he made it clear what would be a good learning artifact based on his views on learning environments: a simplification of real life. Based on Dewey's views, a good learning object should help children feel a part of the adult world, the real world. Dewey's views created a revolution in early childhood environments. Children-size real-world artifacts were developed, like kitchen appliances, kitchen tools, plates, cups, and play food. Costumes for children to dress-up as firefighters, policeman, construction workers or doctors became a popular toy. A 'Dewey Artifact' would be one that is safe for children, fit to children's dimensions, and enable them to freely, independently, pretend in a participatory way they are part of the adult world.

I term Dewey's class "***Reality Role Play***".

The design spirit of these Learning Object classes, Froebel's "Construction & Design", Montessori's "Conceptual Manipulation", and Dewey's "Reality Role Play", has clearly influenced the toy design world in the 20^{th} century. Figure 9 below shows a few modern toys (or learning materials) and how they are sorted into the Learning Object classification I propose.

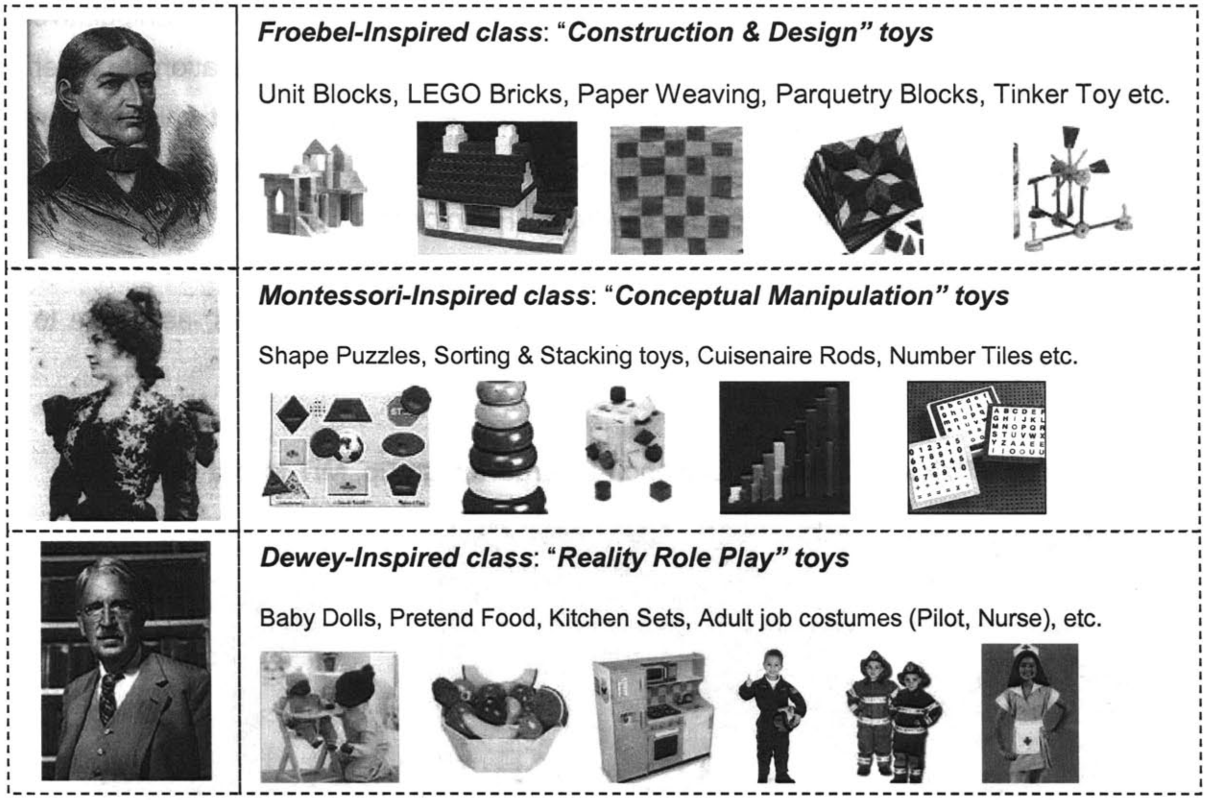


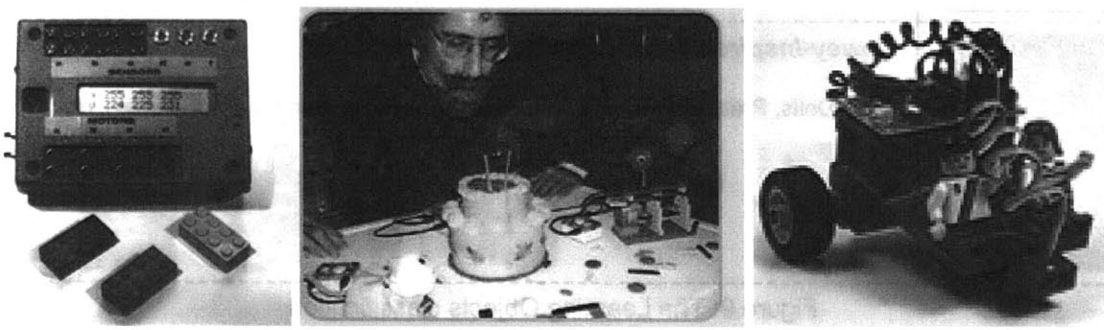
Figure 9: The Learning Objects classification

RELATED WORKS

In 1998, Resnick introduced "Digital Manipulatives", a new breed of manipulative materials. Resnick writes: "These new manipulatives -- with computational power embedded inside -- are designed to expand the range of concepts that children can explore through direct manipulation, enabling children to learn concepts that were previously considered 'too advanced' for children." (Resnick et al. 1998).

The following is an overview of research prototypes that like FlowBlocks, associate to the Digital Manipulatives field.

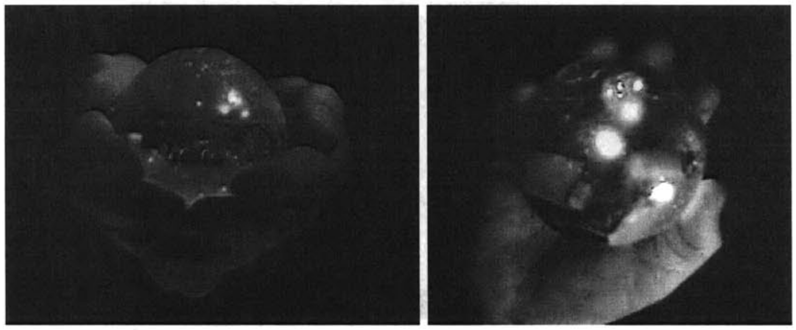
Programmable Bricks / Crickets: Lifelong Kindergarten group, MIT Media Lab



The Programmable Brick and its predecessor the Cricket are tiny computers (Resnick 1998) that control motors, lights, sounds, and receive information from sensors (Martin, 1994; Resnick, 1996a). With the Cricket system, children can use a special visual programming language to create electro-mechanical creations, such as robotic creatures, kinetic sculptures, simple scientific instruments, and custom-made toys. Developed at MIT's Media Lab Lifelong Kindergarten group, Programmable Bricks and later on Crickets empower children to become designers, scientists, and artists at the same time (Resnick, 2000).

Resnick reports (Resnick, 1996b) how children use Cricket to learn about concepts such as feedback and control (when creating a robotic dinosaur that attracts to flashing light) or about general principles of communication (when designing a "protocol" for communicating creatures).

BitBall: Lifelong Kindergarten group, MIT Media Lab

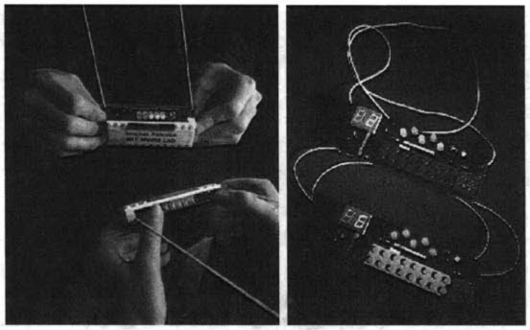


The BitBall (Resnick 1998), a programmable ball, uses its internal acceleration sensor to map acceleration in real-time to different mediums, such as sound and light. Children themselves change the BitBall programs and can customize the mapping. In the process of play and programming, children can learn about the abstract concept of acceleration in a playful way. Resnick reports that a group of university students could not apply their physics classroom knowledge to a real-world context: they tried to find the top of a ball's trajectory based on its acceleration data alone. Using the BitBall they learned that it is impossible to find it from acceleration data alone.

Programmable Beads: Lifelong Kindergarten group, MIT Media Lab

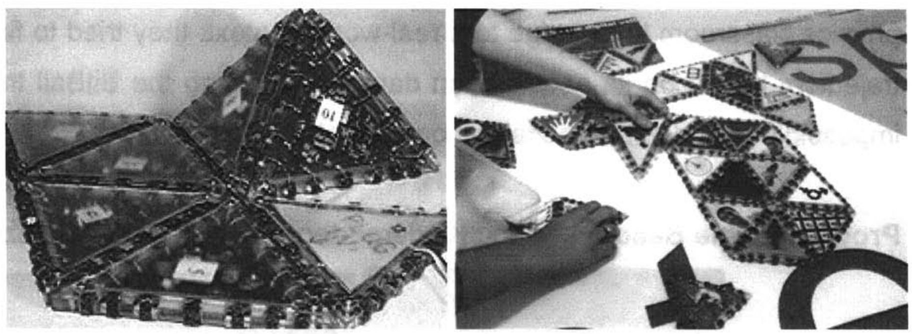
The programmable beads (Resnick 1998) help children control dynamic light patterns in electronic beads units, and in the process learn about concepts such as emergent phenomena.

Thinking Tags: Lifelong Kindergarten group, MIT Media Lab



The Thinking Tags (Resnick 1998), a computational version of the traditional nametag, enables children to become active participants in simulations, and in the process learn about systems concepts and social networks ideas.

Triangles: Tangible Media group, MIT Media Lab

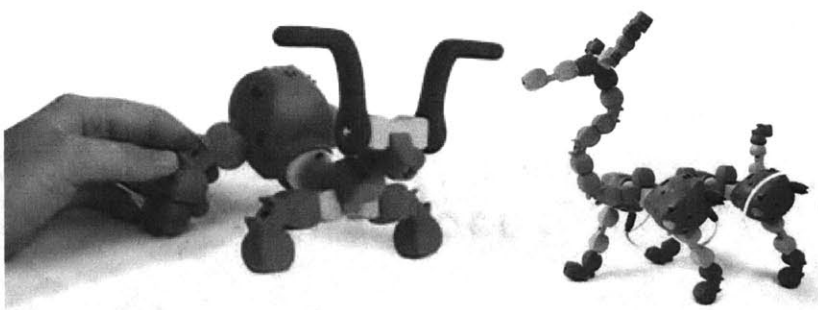


Triangles (Matthew et al., 1998) is a new form of computer interface that uses physical objects to embody digital information. Triangles are a set of triangular-shaped plastic shapes, with embedded computation, that enable users to create both two and three-dimensional patterns. The triangles connect together both physically and digitally with magnetic, conducting connectors. Triangles were tested as a non-linear story telling tool, a media configuration system, and an artistic expression material.

Curlybot: Tangible Media group, MIT Media Lab

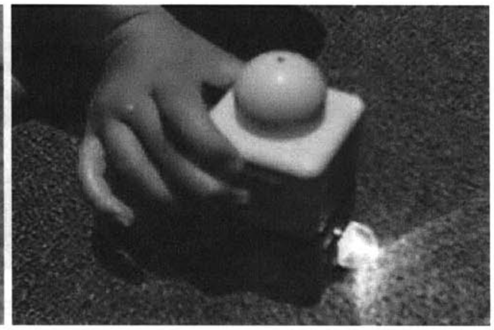
Curlybot (Frei et al. 2000) is a toy that can record and playback physical motion. As one plays with it, it remembers how it has been moved and can replay that movement with all the intricacies of the original gesture; every pause, acceleration, and even the shaking in the user's hand, is recorded. Curlybot then repeats that gesture indefinitely creating beautiful and expressive patterns. Using Curlybot, children can explore mathematical concepts such as differential geometry, or computational concepts such as programming by example.

Topobo: Tangible Media group, MIT Media Lab



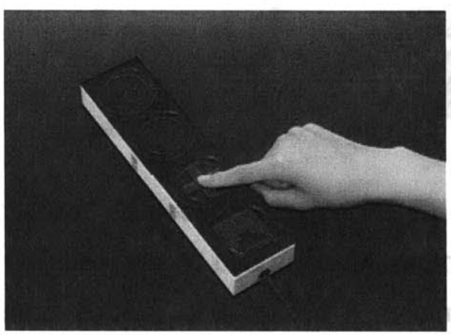
Topobo (Parkes and Raffle, in press) is a 3D constructive assembly system, enabling children to record and playback physical motion. Motions can be created and refined by pulling, twisting, and stretching. Topobo makes it possible to quickly create walking biomorphic forms like animals and skeletons, animated 3D patterns, and dynamic surfaces. Typical Topobo creations would be a walking bug, dog, or moose.

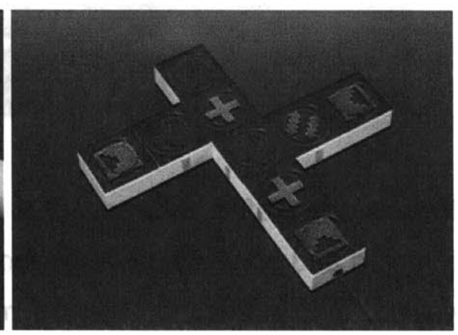
Electronic Duplo Blocks*:* University of Queensland, Australia



Aimed at preschoolers, the Electronic Blocks (Wyeth, 2001) are tangible programming elements mounted inside LEGO Duplo blocks. Using sensor, logic, and action blocks young children create interactive devices such as a light block that activates when clapping or a motion block that moves when light is detected. The Electronics Blocks strength is in its simplicity, enabling very young children to independently create different devices and in the process explore core concepts of logic and programming. Wyeth reports that older children (elementary and middle school students) could build more sophisticated creations, such as towers of blocks that "talked" to each other, alarm clocks and cars that could count.

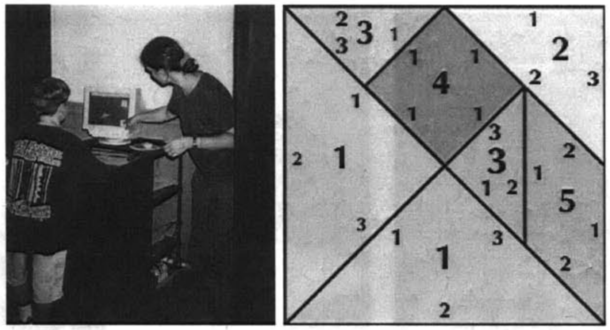
Block Jam*:* Sony Interaction Lab





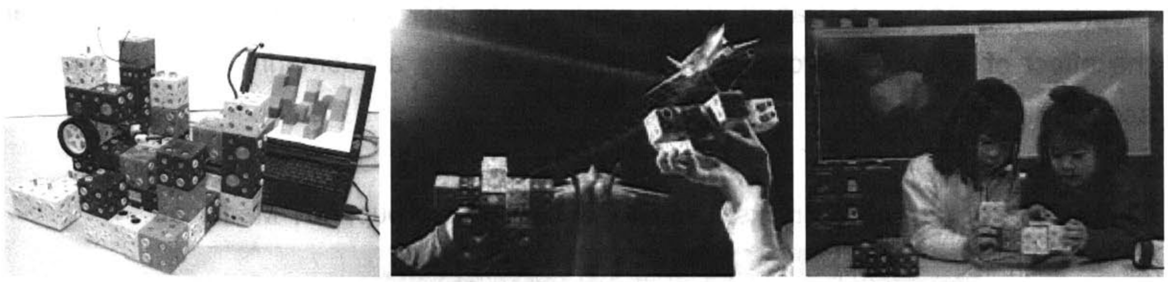
BlockJam (Newton-Dunn et al. 2003) is a block interface for interactive music creation. Block Jam developers define it as a Modular Tangible Interface that is 'Functionally Homogeneous' vs. 'Functionally Heterogeneous' - meaning there is one type of physical artifact with a single function rather than different physical artifacts each holding a different function. Block Jam was not designed to help people understand what the building blocks of a musical sequence are, but was rather designed to make it easier to construct a musical sequence in an expressive process.

TICLE: Brooklyn College



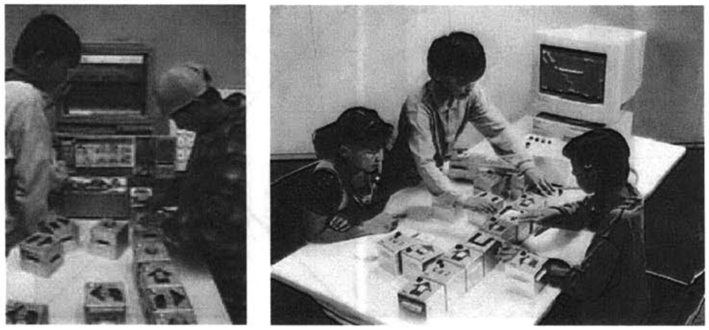
TICLE (Scarlatos 2002) is a computer-vision system that tracks children's play with the Chinese geometry puzzle Tangram. The system scaffolds the play process with hints in real-time. TICLE focuses on scaffolding the play process with the Tangram puzzle, and in the same way, could scaffold children's play with other manipulatives.

ActiveCube: Osaka University



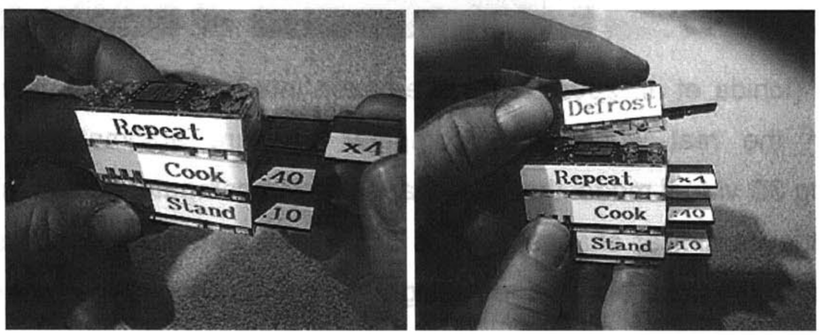
ActiveCubes (Ichida et al. 2004) is a cube-based interface allowing users to build 3D structures in the real world while computer software automatically generates a corresponding 3D virtual model that is displayed on the computer screen. In addition, the computer retrieves similar shapes from its 3D models database, such as an airplane, house, or car. ActiveCube encourages design and construction of real-world objects

AlgoBlock: Suzuki and Kato



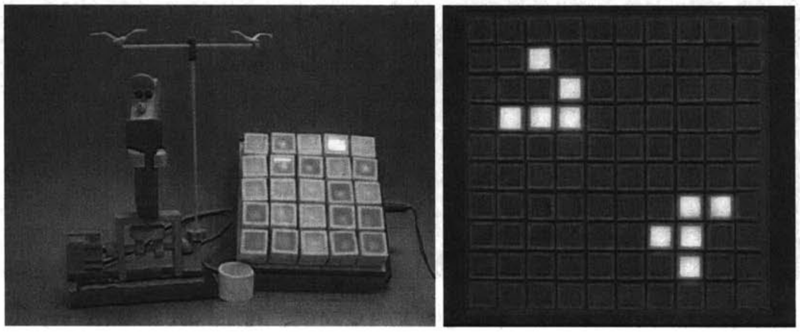
Suzuki and Kato, developers of the AlgoBlock system (Suzuki and Kato 1995), coined the term "Tangible Programming". They developed AlgoBlock to study collaborative problem solving. The AlgoBlock system consisted of a collection of relatively large computational building blocks (approximately 15-cm cubes) that children used to direct a submarine through an underwater maze. Their language was very similar to the Logo programming language (Papert 1971). Although the task of programming was physical, the effect of running a program was "virtual": guiding a submarine on the computer screen.

Tangible Programming Bricks: Lifelong Kindergarten group, MIT Media lab



Tim McNerney's Tangible Programming Bricks (McNerney 2004) are physical building blocks for constructing simple programs, helping children to explore computation and develop their scientific thinking.

Smart Tiles: The Craft Technology Group, University of Colorado at Boulder

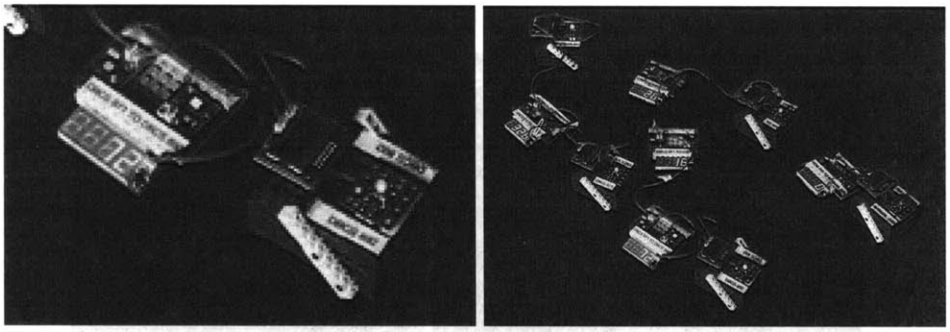


Smart Tiles (Elumeze 2005) are small, computationally-controlled pieces that can be assembled into an array to create complex and beautiful dynamical patterns. The Tiles are essentially tiny LED-equipped "boxes", programmable by the user, that can be placed into slots within the larger array; the sorts of programs that one writes for the tiles are those typical of cellular automata (such as Conway's "Game of Life" system). The tiles also include piezoelectric disks, making them interactive; for instance, one can program a tile so that it will change its color when it is tapped gently by the user.

Boda Blocks: The Craft Technology Group, University of Colorado at Boulder

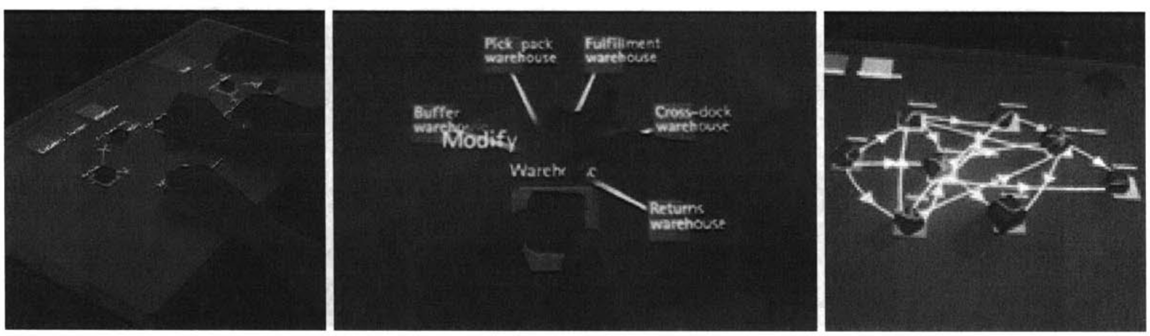
The Boda Blocks (Buechley 2007) kit consists of a set of blocks which can be linked together into three-dimensional structures capable of displaying dynamic patterns. Currently, a desktop application lets users program the blocks with cellular automaton rules, allowing them to build a variety of three-dimensional cellular automata. Users can build structures with the blocks and connectors, set an initial configuration on the construction by turning the blocks on or off, and then watch the resulting cellular automaton evolve as a pattern of lights moving through the construction.

Tangible Modeling Toolkit: MIT Media Lab



In 2002, Tim Gorton introduced "Tangible Toolkits for Reflective Systems Modeling" (Gorton, 2003). Gorton presents a hardware and software infrastructure that enables developers to create modeling toolkits for specific dynamic systems. Using his infrastructure, Gorton created two toolkits, one simulating mail flow in a USPS distribution facility, and the other simulating computer network chat model. In two case studies performed with these toolkits, Gorton observed that the tangible and decentralized aspects of the toolkits promoted discussion, interaction, excitement and sense of ownership among the case studies' participants.

Sensetable: Tangible Media Group, MIT Media Lab



Sensetable is an interactive tabletop platform developed at the tangible Media Group at MIT's Media Lab (Patten, 2001). Sensetable is a system that wirelessly tracks the positions of multiple objects on a flat display surface quickly and accurately. The tracked objects have a digital state, which can be controlled by physically modifying them using dials or tokens.

Several applications were created on top of the Sensetable platform, including business supply chain visualization using system dynamics simulation; IP networked design workbench; and CircuiTUI, an electronics circuit design and simulation tool.

The Supply Chain Visualization (SCVis) project provides a way for managers to physically construct and interact with models of how products flow between their business, thier suppliers and their customers. It lets managers use complex numerical simulation techniques as part of "what if?" conversations about possible changes to the way they do business. The SCVis system is built on top of the Sensetable platform.

The interface has two parts. One of these lets managers construct models of thier supply chains from scratch. They do this by manipulating physical objects representing various types of factories, warehouses, customers and suppliers on a tabletop surface. A computer tracks the motions of these physical objects, and gives the user feedback using video projection from overhead. As the user creates relationships between the various objects on the table, these relationships are translated into business relationships in a simulation model. This model can be used to develop an understanding of some of the dynamic properties of the supply chain.

The second part of the interface lets users simulate existing supply chain models. One can navigate through a taxonomy of business processes, and select one that is similar to a particular business one would like to learn about. One can then modify that model to make it more similar to the real-world business in question. In addition one can run numerical simulations to understand the dynamic behavior of the supply chain. One can physically tweak parameters in this simulation, and receive real-time feedback about how these changes affect the simulation as a whole.

CHAPTER 4. DESIGNING FLOWNESS: A SIMPLIFIED MODELING LANGUAGE

Flowness is a new modeling language for Systems Thinking, inspired by the Systems Dynamics modeling languages. Two primary modeling languages have been developed for Systems Dynamics: (1) Stocks & Flows, and (2) Causal Loops Diagrams. In the background chapter of this thesis I have introduced both languages. In this chapter I will focus on the advantages and disadvantages of each language, introduce my design approach and the language I have created – Flowness: a simplified Systems Thinking modeling language.

Stocks & Flows (S&F) and Causal Loops Diagrams (CLD) are very different languages. Each has its own advantages and disadvantages. Generally speaking, S&F is not intuitive-to-learn, but is computationally simulate-able. In contrast, CLD is very intuitive-to-use, but is not computationally simulate-able. I designed Flowness to be both computationally simulate-able and intuitive-to-learn (see Figure 10 below).

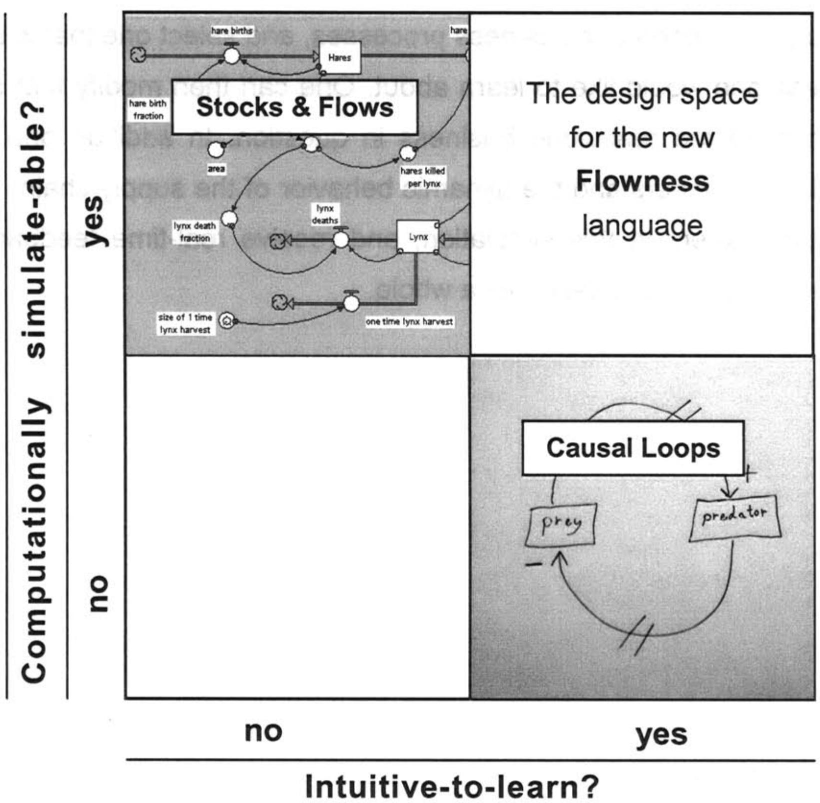


Figure 10: Flowness is designed to be both intuitive-to-learn (like the Causal Loops Diagrams language) and computationally simulate-able (like the Stocks & Flows

S&F is a powerful language for experts. There are two common software tools allowing users to visually create and simulate S&F models (STELLA made by isee systems and Vensim made by Ventana systems). The Flowness language is targeted towards novices and children rather than experts, and strives to make the core concepts of Systems Thinking more accessible.

There are many concepts covered in the Systems Thinking literature. I have decided to focus on the following concepts, as they can serve as the core "conceptual building blocks" for computer simulation:

- **Stock**: a stock (or "level") is a quantity that accumulates over time by inflows and/or depleted by outflows. Stocks can only be changed via flows. Stocks have a certain value at each moment of time, which is the accumulated inflow minus the accumulated outflow. For example, a stock can be the level of a population, the level of water in a bathtub, or the anger level of a person.

- **Flow**: a flow (or "rate") changes a stock over time. Inflows are adding to the stock, and Outflows are subtracting from the stock. Flows are measured over a certain interval of time. For example, the number of births per day or month, the amount of water poured from the faucet per second, or the number of annoying incidents per day (the Inflow to the "anger level" stock).

- **Feedback influence**: Flows influence stocks directly, by adding or subtracting "stuff" from the stock at any given moment. A Feedback connection happens when the level of a stock influences one of the flows. The influence happens when the stock's current value is reported to one of the flows, influencing the flows to increase/decrease their rate based on the reported value. In turn, the flow is influencing the stock, which is turn influence the flow again. For example, if a certain human population increases, it means that over time there are more child-bearing couples, which means there are potentially more babies born. So the "population" stock influenced the "birth-rate" inflow. More births means increase in population, which in turn means increase in birth-rate and vice versa. This type of feedback, that reinforces or amplifies a system, is called **Positive Feedback**. The other type of feedback is called **Negative Feedback**, and occurs when a certain system is balanced or regulated by its own processes or influences. One example is a climate control system: the system generates hot (or cold) air until the thermostat's temperature measurement sends a "message" that the desired level has been reached, then hot (or cold) air generation is paused, until the thermostats sends another message to resume. This way the air temperature is kept at a desired level.

Table 11 below analyzes the strengths and weaknesses of the existing modeling languages, with focus on the language core strengths and the novice user experience.

	S&F	**CLD**
Which concepts are made salient to novices?	Stocks Inflows Outflows	Positive feedback Negative feedback
Is the language simulate-able?	Yes	No
Can the language simulate incomplete models?	No	No
What is the previous knowledge required from novices?	Math: Arithmetic & Elementary Algebra	None

Figure 11: Comparing existing Systems Thinking languages from the novice user perspective

I defined four principles to guide the design process of the Flowness language.

1. **Focus on the essence**: the language should make the core Systems Thinking concepts salient to novices: Stocks; Inflows, Outflows; Loop-based thinking; 1st and 2nd order positive feedback & negative feedback loops. The trade-off will be compromising accuracy and advanced concepts/features.

2. **Make the language computationally simulate-able**: the language must be formal enough to be simulated using digital computation.

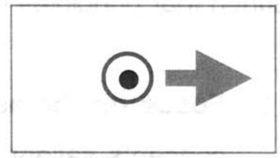
3. **Create a forgiving language**: any possible configuration should result in a successful simulation. The language should allow users to simulate partial models, to make incomplete models and still experience the model's simulation. The simulation process must not require a formal process that can fail (like a compiler for a programming language).

4. **Require minimal background knowledge**: novices should be able to create models with no formal knowledge in Arithmetic or Algebra beyond counting. In addition, no prior knowledge of programming or any of the Systems Thinking concepts is required.

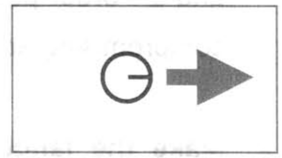
Flowness elements

The Flowness modeling language is based on four conceptual elements: Inflow elements, Flow elements, Accumulator elements, and Feedback wires. These four elements work as an integrated system and can be connected in different configurations, creating models that reveal the mechanism underlying constant change, such as: direct cause & effect (short term consequences), delayed direct cause & effect (long term consequences), closed and open systems (conservation of matter vs. "cradle-to-grave" systems), reinforcing growth due to positive feedback loops (exponential growth), balanced growth due to negative feedback loops (goal-based growth), probabilistic causality (side effects), dynamic equilibrium, oscillation, and more.

Inflow elements are the elements that generate the light signal; they start the chain reaction of passing the light signal from element to element. There are two types of Inflow elements: *Inflow-Discrete* and *Inflow-Continuous*. The *Inflow-Discrete* has a button to generate a discrete light signal and send it out to the next element through the output port. The *Inflow-Continuous* element has a dial to generate a sequence of light signals and send them out to the next element. The dial can generate slower or faster sequences light signals.



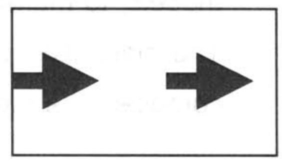
Inflow-Discrete



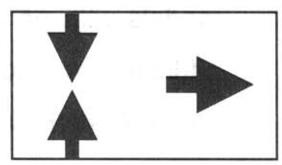
Inflow-Continuous

Flow elements are the elements that pass the light, that create a path for the light to travel through. When a Flow element receives a light signal from the previous element, it blinks its input light, delays the signal, blinks its output lights, and pass the signal to the next element through the output port. The blinking lights create an illusion of a light "token" moving through the element.

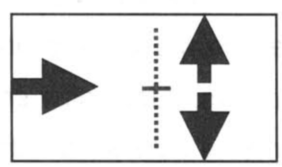
There are three types of Flow elements: *Flow-Straight*, *Flow-Turn*, and *Flow-Distribute*. The *Flow-Straight* element passes the light in a straight line from input on the back to output on the front. The *Flow-Turn* element can receive input from one of two possible input ports, one on each side. Then it passes the light signal in a "90 degree" angle from input to output. The *Flow-Distribute* element can receive input from the back, like the *Flow-Straight* element, but can distribute the light signal to one of its two output ports: left or right. The *Flow-Distribute* element has a user-controlled slider that determines how the light signal will be distributed. The options are: always left, always right, 50% of the times turn left and the other 50% turn right, 25% left and 75% right, or 75% left and 25% right.



Flow-Straight

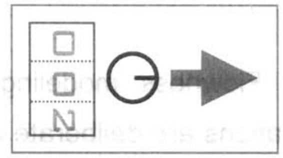


Flow-Turn



Flow-Distribute

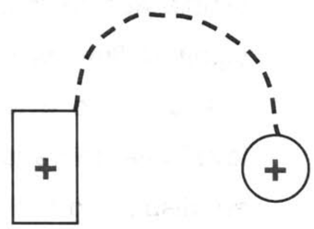
Accumulator & Outflow elements are the elements that store & accumulate the incoming light signal, and then release the light signal to the next elements. The *Accumulator* has a numeric display that displays how many "lights" have been accumulated so far. It also has an *Outflow* dial, similar to the *Inflow-Continuous* element's dial. The *Outflow* can "drain" the *Accumulator* by sending a sequence of light signals out from the stored level to the next element. When the *Accumulator* is empty the Outflow sends nothing. The *Accumulator & Outflow* elements can receive and release lights simultaneously.



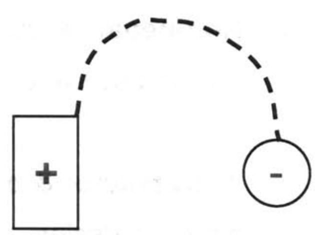
Accumulator & Outflow

The *Outflow* is built-into the *Accumulator* element to make it easier to connect other elements to the *Accumulator*. This careful design decision is compromising "model clarity" in favor of a more playful and "forgiving" language. The *Accumulator & Outflow* design allows other *Accumulators* or *Flow* elements to follow. An Accumulator-only design would limit the options and allow only one element to follow - the *Outflow* element. The current design promotes an intuitive way of making models.

Influence connections are connection wires that connect between the Accumulator display module and the two continuous dials in the system: the *Inflow-Continuous* dial and the Accumulator's *Outflow* dial. When a Feedback wire is connected, the Accumulator's current level is sent through it, reporting the amount back into the system (feed-back), and used by the Inflow/Outflow element to generate the appropriate rate for the outgoing light sequence. There are two types of Feedback wires, Blue and Red. The Blue-Feedback wire reports the current amount from the Accumulator, so more in the Accumulator will result in more flow in the generated light sequence ("more-is-more "relationship). The Red-Feedback wire report the (max_amount – current_amount) from the Accumulator, so more in the Accumulator will result in less flow in the generated light sequence ("more-is-less" relationship).



More-is-More Cable



More-is-Less Cable

Language Limitations

The Flowness modeling language has limitations on several levels. Most of the limitations are deliberate design decisions that compromise accuracy or model variety in favor of simplicity and ease-of-use for novices.

- **Parameters** are an integral element in Stock & Flow modeling, I have decided to omit parameters from the Flowness language. Without parameters the range of possible models is smaller, and simulation accuracy, credibility, and level of control is compromised. I made this critical design decision to enhance the language simplicity and focus on the essence of dynamic behavior.

- **Non-linearities** are a key component of advanced Stock & Flow models and are integral to create more realistic simulations. Non-linearities are modeled using mathematical functions such as step functions. Since I preferred to keep the Flowness modeling process simple, non-linearities are not available in the Flowness language.

- **Accumulation vs. integration**: in my implementation, the Accumulators perform simple accumulation - Integration with a time factor (dt) of 1. Every incoming signal (Inflow) is increasing the Accumulator's "current-level" internal variable by one unit and every outgoing signal is decreasing the Accumulator's "current-level" internal variable by one unit. In the type of simulations and accuracy level I am displaying to the user there is no need for a smaller time factor (the common one used in System Dynamics simulations is 0.1).

- **Non-negative Accumulators:** in my implementation, the Accumulators are always positive or zero, so negative stocks are impossible to model.

- **Accumulator & outflow merged**: I made a significant design decision about the physical design of the system and decided to merge the Accumulator and Outflow into one element. This decision compromises conceptual clarity but increase modeling ease-of-use and tinker-ability. The limitations this design decision introduces include: conceptual misconception that all stocks have an outflow; inability to model stock without outflow; and decreased visual attention to the stock concept.

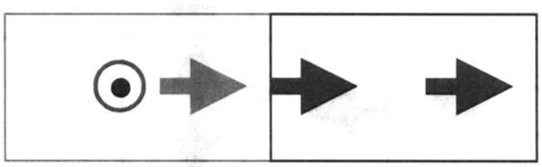
- **No fractional feedback**: the feedbacks in Flowness are always 100% feedback, there is no option to create fractional feedback, or to multiply a feedback with a Flow parameter.

- **Forced delays**: when creating a Flowness visual model, the light visualization in each element creates an inherent delay, so any model must include some delays in it. In Stock & Flow models signal transfer is not visualized, and therefore can be immediate.

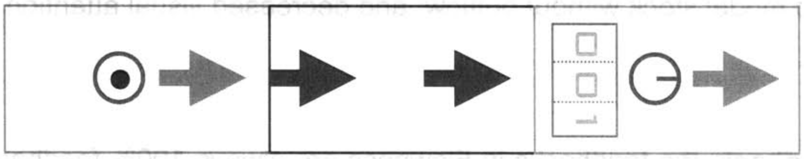
Making Flowness models

Putting several Flowness elements together forms Flowness models, which are simulate-able. All models require an Inflow element, at least as a starting point. Later on, when light is already flowing through the system, an Inflow element can be disconnected keeping the simulation intact.

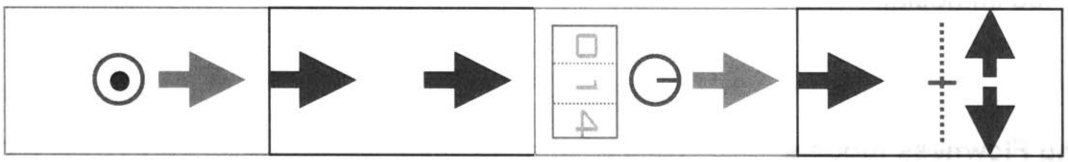
Here is a step-by-step process of making one possible model:



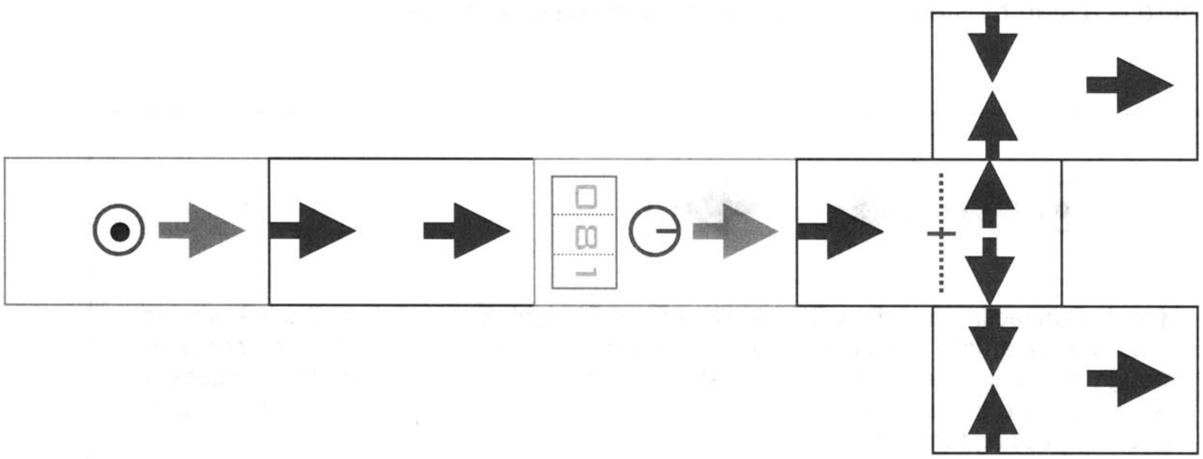
Step 1: Connecting an Inflow-Discrete to a Flow-Straight. Every click on the Inflow's red button sends a light "token" out from the Inflow and into the Straight. The light goes through the straight element and is lost by being sent out to nothing. The process is visible because the arrows are blinking in a sequence, creating the illusion that a light "token" is passing through the elements.



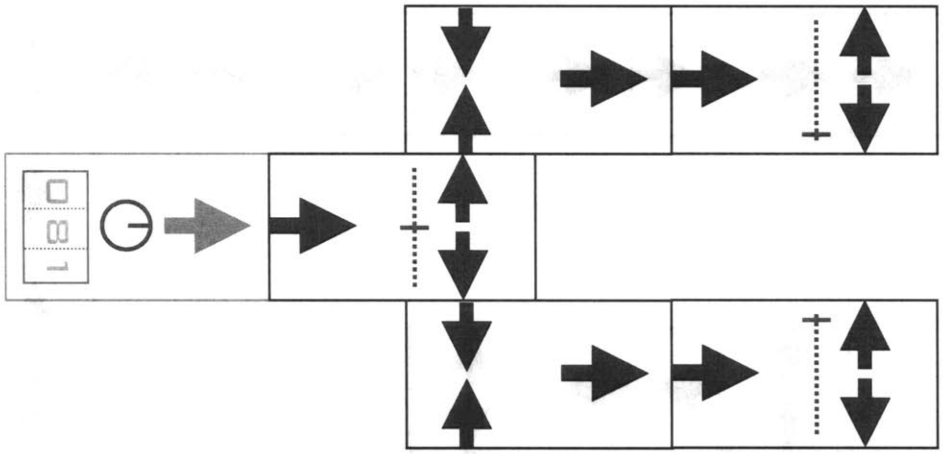
Step 2: Adding an Accumulator after the Straight. Now the light is not lost, but enters into the Accumulator and is stored. The Accumulator display increments by one, displaying how many light "tokens" have been stored so far. Every time the button is clicked on the Inflow, the light passes through the Straight and into the Accumulator. If the Outflow dial (in the Accumulator element) is turned, lights start to flow out from the Accumulator to the next element. The more one turns the Outflow dial, the faster the Accumulator is being "drained" and the faster the rate of flow out from the Accumulator. In this case the light is lost because there is no element connected after the Accumulator.



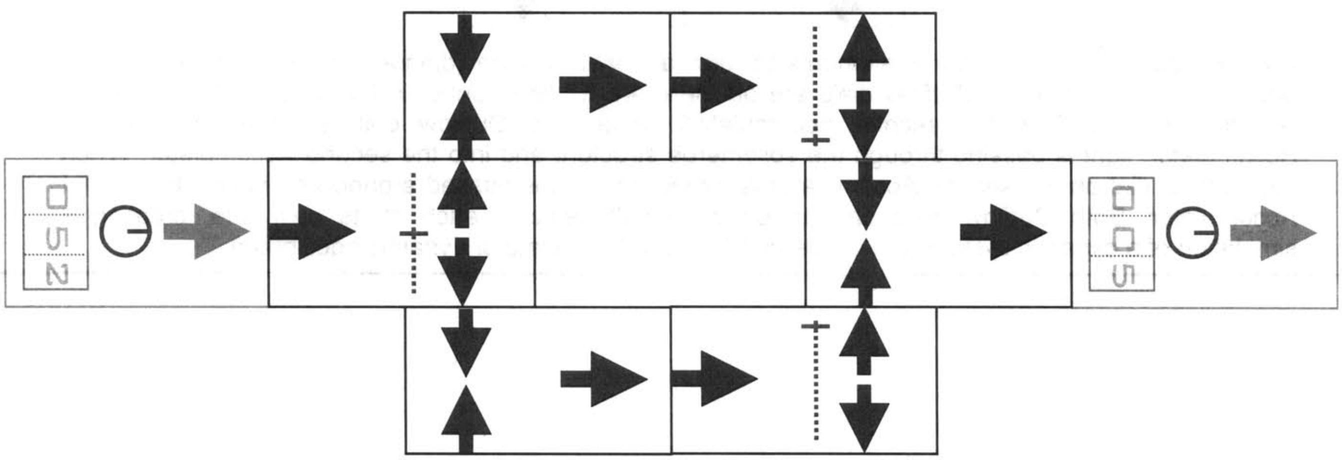
Step 3: Adding a Distributor after the Accumulator. The light flows out from the Accumulator and into the Distributor. The Distributor slider is set to the middle, so the light will be distributed with a probability of 50% to turn left or right. The more the Outflow dial is turned, the faster the light will flow through the Distributor. When the Accumulator becomes empty, the flow of lights stops. Clicking the red button on the Inflow element will generate more light "tokens" and will increase the accumulator's stored level. The Distributor can distribute the light at different probabilities: 100% to the left, 75% left and 25% right, 50% left and 50% right, 25% left and 75% right, and 100% to the right.



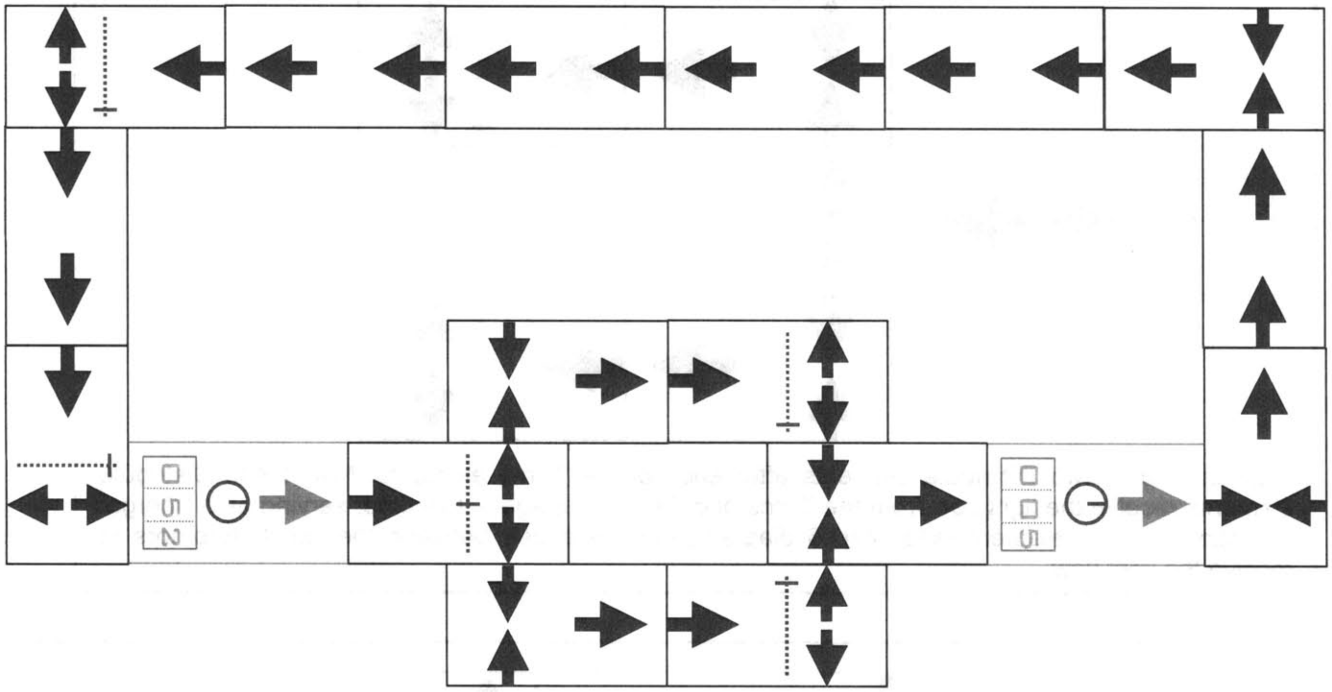
Step 4: Adding two Turn elements at each side of the Distributor. Now these Turn elements can receive the light flow from the Distributor and direct it forward. The button can be pressed many times to increase the Accumulator's level, in this case, the button was pressed 81 times. Now, if desired, the Inflow element can be removed, and the Accumulator would still be capable of sending lights out through the Outflow until the Accumulator will become empty.



Step 5: Adding two Distribute elements after each of the Turns elements. Now these Distribute elements receive the light flow from the Turns and distribute it again, this time, serving as a "merge" operation. A Turn element (see Step 6 diagram) can be added between the two Distributors to receive the light flow.



Step 6: Adding the Turn element in between the two Distributors, and then an Accumulator after the Turn. Now the light flow exits the first Accumulator, splits to two paths and merges back into one, and then is stored in another Accumulator. This simulation emphasizes the "conservation of signal" in the system, because when the process ends the amount in the second Accumulator's display will be equal to the initial amount in the first Accumulator. At this stage, the ambitious builder might be interested to go on and create a closed system that "recycles" the light signal (see Step 7).



Step 7: Adding many additional elements to form a closed system (diagram reduced in size to fit in page). For example if the Outflow dials are off there are 57 light "units" in the system (52 in the first Accumulator and 5 in the second Accumulator). When the Outflow dial is turned on the first Accumulator, light is passing through the split/merge structure and into the second Accumulator. When the Outflow dial on the second Accumulator is turned on, light is passed around and back into the first Accumulator. Both Outflow dials can turned on simultaneously, each at its own rate, creating a simulation of a dynamic system with conserved "material" in a state of dynamic equilibrium.

Flowness Universal Models:
12 models that uncover the dynamics of everyday life

Within the Systems Thinking and Systems Dynamics communities there has been an on-going effort to highlight key models, ones that generate common behavior of systems in our everyday lives. Jay Forrester created a set of "Generic Structures", used particularly for education (Forrester 1961, 1969, 1971). Peter Senge, in his seminal book "The Fifth Discipline", published a set of "Systems Archetypes" using the Causal Loop Diagrams language (Senge 1990). Senge's Archetypes map common patterns we experience in life in general and organizations in particular. John Sterman, in his "Business Dynamics" book, mapped models that generate the most common dynamic behavior such as goal-seeking growth or decline, overshoot and collapse, and different oscillations (Sterman 2000).

These "Generic Structures" (in Forrester's terms) or Nature's Templates (in Senge's terms) are important because they increase our awareness to the causal patterns that underline the complexity in our daily lives. From the dynamic flow of physical matter such as water, air, packages or cars, to psychological cycles such as depression of the "ups and downs" of our lives, to sociological cycles such as fashion trends or social influence, to economics concepts such as interest or price dynamics, to medical issues such as drug addiction and the spread of viruses: the complex behavior around us can be explained with a limited set of causal patterns.

I used the Flowness language to create a set of Generic Structures that introduce key Systems Thinking concepts. My set of Generic Structures is heavily based on the existing models from Forrester, Senge, Sterman, and others. My contribution in this area is: simplified, simulate-able models that are appropriate for novices (no background needed in Algebra or Systems Dynamics), presented in a gradual way and covering core concepts of systems thinking. I term my set of Generic Structures the "Flowness Universal Models", or FUMs.

In the following pages I present the Flowness Universal Models (FUMs), arranged into four categories: *the **Basic Flow Stream** category*; *the **Chains of Basic Flow Streams** category*; the ***One-way Influence between Flow Streams** and the **Feedback influence***

in Flow Stream *category.* FUMs are presented using a configuration of Flowness elements, a step-by-step description of the simulation, a set of concepts introduced in that FUM, and a thematic example that matches the behavior of the model (example is the consequences of trash accumulation).

The FUMs purpose is to help novices build a gradual understanding of the dynamic world around them. Each model builds on the previous one while introducing new concepts and new patterns of behavior, progressing from simple to advanced models. Clearly, these models are not accurate models of reality. As John Sterman has said: every model is wrong. The Flowness language was not designed to create predictions of reality or to accurately simulate real-life situations. Rather, the language was designed to highlight core concepts in Systems Thinking in a way that will help novices develop intuitive understanding of these concepts.

In the Fifth Discipline book (Senge 1990), Peter Senge presents the concepts Individual Mental Models as well as group Mental Models. The inspiration to develop FUMs came from the hope that intuitive simulate-able models can help individuals as well as groups experience the simulated casual pattern, learn the Universal Model, and over time assimilate the models towards a possible creation of new individual or group Mental Models.

In this section I introduce a summary of each of the Flowness Universal Models, followed by a detailed description with models diagrams and real-life simulation examples.

Figure 12: Tinkering with Universal Model 2 – the Basic Flow Stream

Basic Flow Stream

FUM1. **Continuous Accumulation:** Inflow leads to Accumulation. Increased Inflow rate will increase Accumulation's rate-of-change.

FUM2. **The Basic Flow Stream (BFS)**: Inflow, Accumulation, Outflow. Both Inflow and Outflow increase/decrease the Accumulation's rate-of-change simultaneously.

Chains of Flow Streams

FUM3. **Open Chain**: several Accumulators connected as a linear chain, Outflow of one Accumulator serves as the Inflow of the next. A cradle-to-grave system.

FUM4. **Probabilistic Distribution**: a "fork-style" chain, in which one Basic Flow Stream is connected to two additional Basic Flow Streams, so material is distributed from one Stream to the next ones in a probabilistic way.

FUM5. **Closed Chain**: several Accumulators connected in a way that forms a closed structure, forming a cycle in which "material" is conserved. A cradle-to-cradle system.

One-way Influence between Flow Streams

FUM6. **One Flow Stream Reinforces Another**: two Basic Flow Systems connected with a "more-is-more" wire in a reinforcing relationship. The one-way influence creates a fixed relationship in which more in one Accumulator leads to increased Inflow into the other Accumulator. More in one BFS leads to more in another BFS.

FUM7. **One Stream Regulates Another**: two Basic Flow Systems connected with a "more-is-more" wire is a regulating relationship. The one-way influence creates a fixed relationship in which more in one Accumulator leads to increased Outflow out from the other Accumulator. More in one BFS leads to less in another BFS.

Feedback Influence in Flow Streams

FUM8. **Self-Reinforcement**: One BFS with "more-is-more" wire connected back to itself in a reinforcing relationship; more in the Accumulator leads to more Inflow which in turn leads to more in the same Accumulator. A first-order positive feedback system.

FUM9. **Self-Regulation**: One BFS with "more-is-more" wire connected back to itself in a regulating relationship; more in the Accumulator leads to more Outflow which in turn leads to less in the same Accumulator. A first-order negative feedback system.

FUM10. **Mutual Reinforcement**: Two separate BFS connected with two "more-is-more" wires both in a reinforcing relationship; more in one Accumulator leads to more in the Inflow to the other Accumulator, and more in the other Accumulator leads back to more in Inflow to the first Accumulator. So more in one BFS leads to more in the other BFS, which in turn leads to more in the first BFS and back again. A second-order positive feedback system.

FUM11. **Mutual Reinforcement & Regulation (oscillation)**: Two separate BFS connected with two "more-is-more" wires, one in a reinforcing relationship and one in the regulating relationship; more in one Accumulator leads to more in the Inflow to the other Accumulator (increasing it), BUT more in the other Accumulator leads back to more in the Outflow of the first Accumulator (decreasing it). So more in one BFS leads to more in the other BFS, which in turn leads to less in the first BFS and back again. A second-order negative feedback system that simulates oscillation.

FUM12. **Resource Depletion**: two FUMs merged, FUM6 + FUM9. The result is one exponential-growth system (self-reinforcing Flow Stream) depleting a separate linear-growth system (Basic Flow Stream). This FUM is an example for using the FUMs as building blocks to create new casual patterns of more complex systems.

In the following pages I present a detailed description of each of the Flowness Universal Models (FUMs), along with a model diagram and real-life example.

Flowness Universal Model 1 : Continuous Accumulation

Concepts introduced: ***Continuous Flow, Accumulation, Inflow, Rate-of-Change***

Short description: Inflow leads to Accumulation. Increased Inflow rate will increase Accumulation rate-of-change.

Thematic example: People purchase things; people own things.

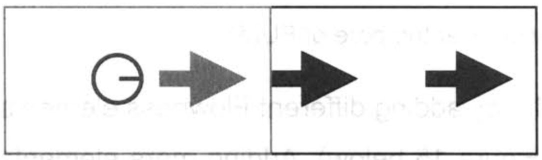


Figure 13: Continuous flow

FUM1 starts with the core concept, the continuous flow of "stuff" from one place to another. In the simulation, the "stuff" is light "units". The light flows in a sequence, in a continuous stream, from the Inflow and out to the next Flowness elements. The dial controls the rate of the generated flow of light. The added Flow-Straight element adds more arrows and therfore helps visualize the light "flowing".

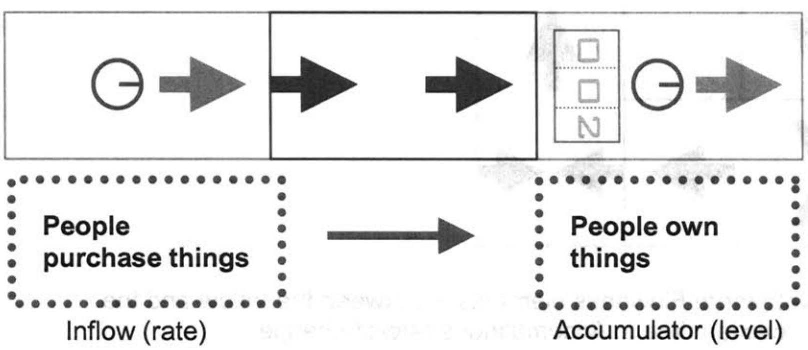


Figure 14a: FUM1 model, analogy using the "purchasing" example

Adding the Accumulator element completes this FUM. The generated stream of lights is flowing into the Accumulator and increasing the Accumulator's current level, displayed in its numeric display. The Accumulator's rate-of-change is determined by rate of incoming flow. A constant rate of inflow would lead to a steady, continuous, linear growth in the accumulation. A changing rate of inflow will lead to changing rate of growth in the accumulator. If the inflow rate is increasing in a linear fashion, the accumulation rate will increase in a geometric fashion.

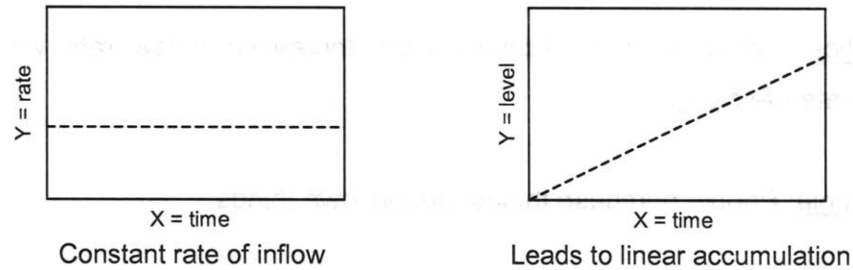


Figure 14b: Rate-of-change simulation is at the core of FUM1

There are many different ways to simulate FUM1, by adding different Flowness elements between the Inflow and the Accumulator (see Figure 15 below). Adding more elements in-between will create a time-delay between the action (turning the Inflow dial) and the reaction (Accumulator rate-of-change increased/decreased).

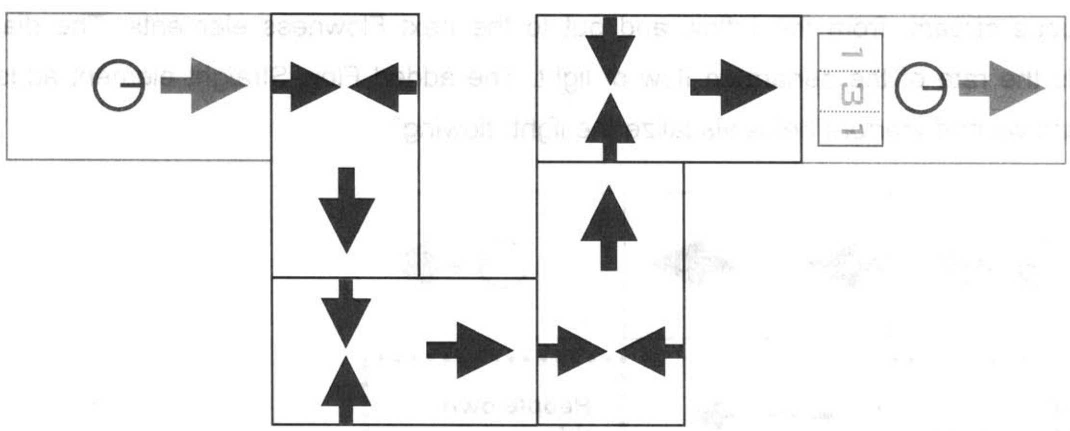


Figure 15: FUM1 simulation with more Flowness elements in between the Inflow and the Accumulator, leads to slower reaction time in Accumulator's rate-of-change.

Flowness Universal Model 2 : Basic Flow Stream

Concepts introduced: ***Outflow, Simlatanuous processes, Continuous change, Rate-of-change with Inflow+Outflow, Dynamic equilibrium, "Dynamic System"***

Short description: Inflow, Accumulation, Outflow. Both Inflow and Outflow increase/decrease the Accumulation rate-of-change simultaneously.

Thematic example: People purchase things; People own and use the things they purchased; people get rid of the things they owned and used.

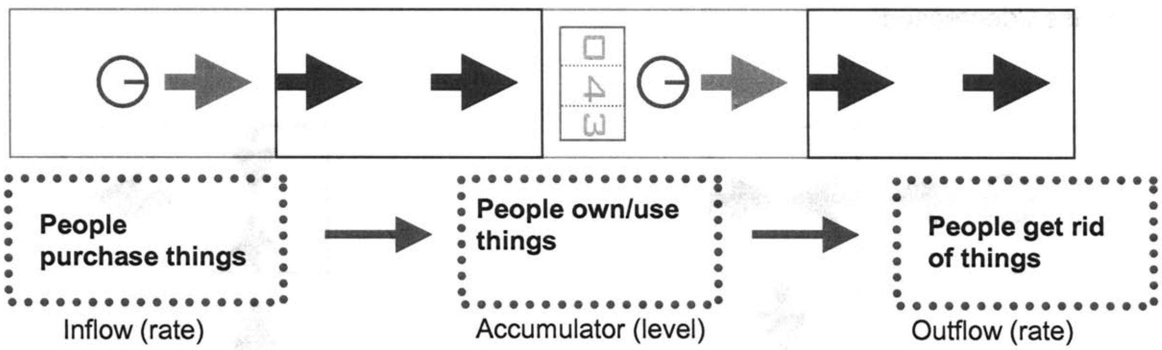


Figure 16: FUM2 simulation of the Basic Flow System; Analogy using the "trash consequences" example.

FUM2 introduces the Outflow concept and the dynamic state of a system with simultaneous rates of Inflow and Outflow. The Outflow dial on the Accumulator element control the outflow rate, which decrease the Accumulator's stored level. As in FUM1, the Inflow dial controls the inflow rate, which increase the Accumulator's stored level. Both rates can be controlled independently, affecting the Accumulator simulatenuously. The added Flow-Straight elements are not essential, but they help visualize the light "flowing" into and out from the Accumulator.

FUM2 enables direct experience with the dynamic state of the Accumulator. More Inflow leads to increase in the Accumulator, more Outflow leads to decrease in the Accumulator. Equal rates of Inflow & Outflow leads to dynamic equilibrium, a dynamic state in which the Accumulator's level does not change, but "light" is continuously flowing into and out from it. Interaction with a FUM2 simulation makes it easier to understand that there are two distinct ways to cause change in Accumulator's level: decreasing the Inflow rate would have the same effect as increasing the Outflow rate (Accumulator level will go down); in the same way, increasing the Inflow would have the same effect as decreasing the Outflow (Accumulator level will go up).

FUM2 represnets one of the most fundamental structures in Systems Thinking, a "dynamic system" that is continuously changing and can not be influenced directly but only through the Inflow and Outflow elements. There are many different ways to simulate FUM2, by adding different Flowness elements between the Inflow and the Accumulator (see Figure 17 below). Adding more elements in-between will create a time-delay between the action (turning the Inflow dial) and the reaction (Accumulator level increased/decreased).

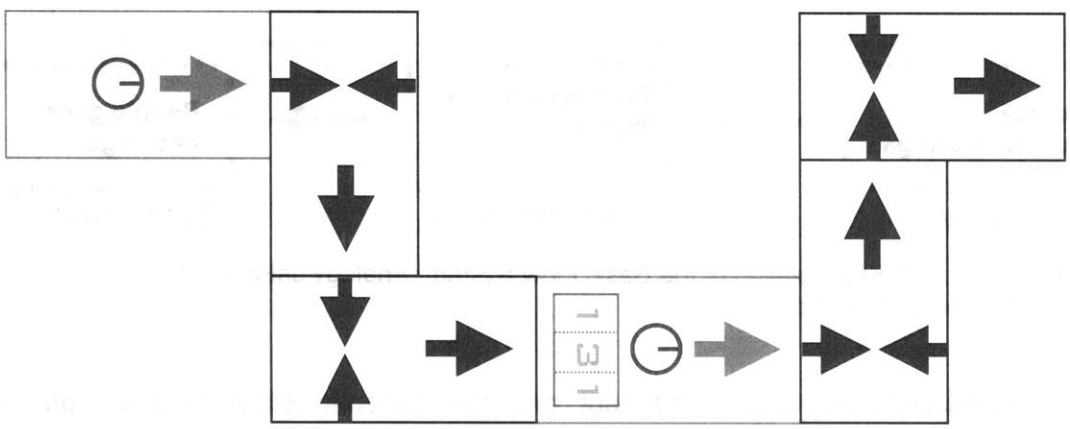


Figure 17: FUM2 simulation with more Flowness elements

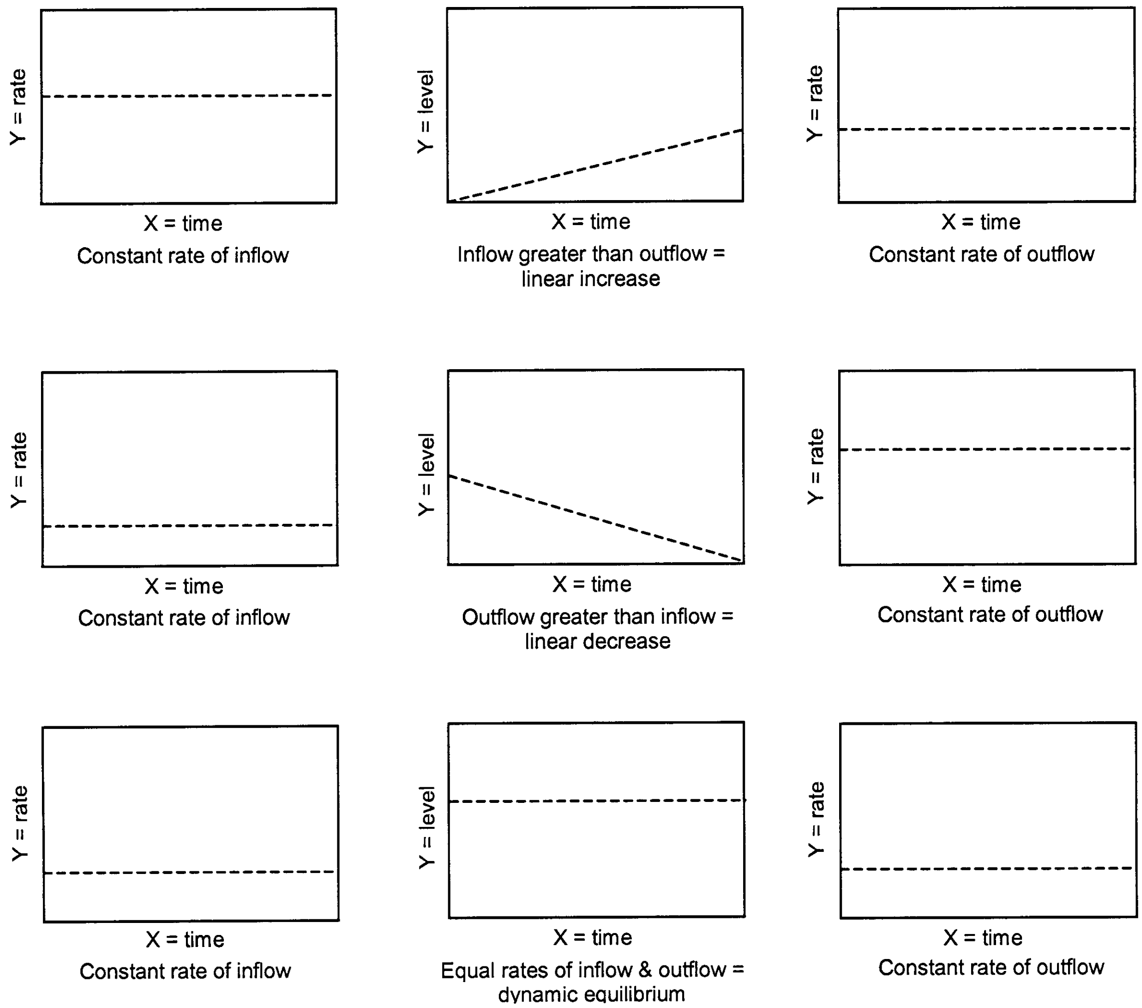


Figure 18: Rate-of-change simulation with both Inflow and Outflow

Flowness Universal Model 3 : Open chain

Concepts introduced: ***Open Chain, non-renewable resource, renewable resource***

Short description: several Accumulators connected as a linear chain, Outflow of one Accumulator serves as the Inflow of the next. A cradle-to-grave system.

Thematic example: People purchase things (per week); People own and use the things they purchased; People get rid of the things they owned and used (per week); Trash accumulates in dumpster; Garbage truck empties dumpster, carries garbage to waste sorting at the Materials Recovery Facility.

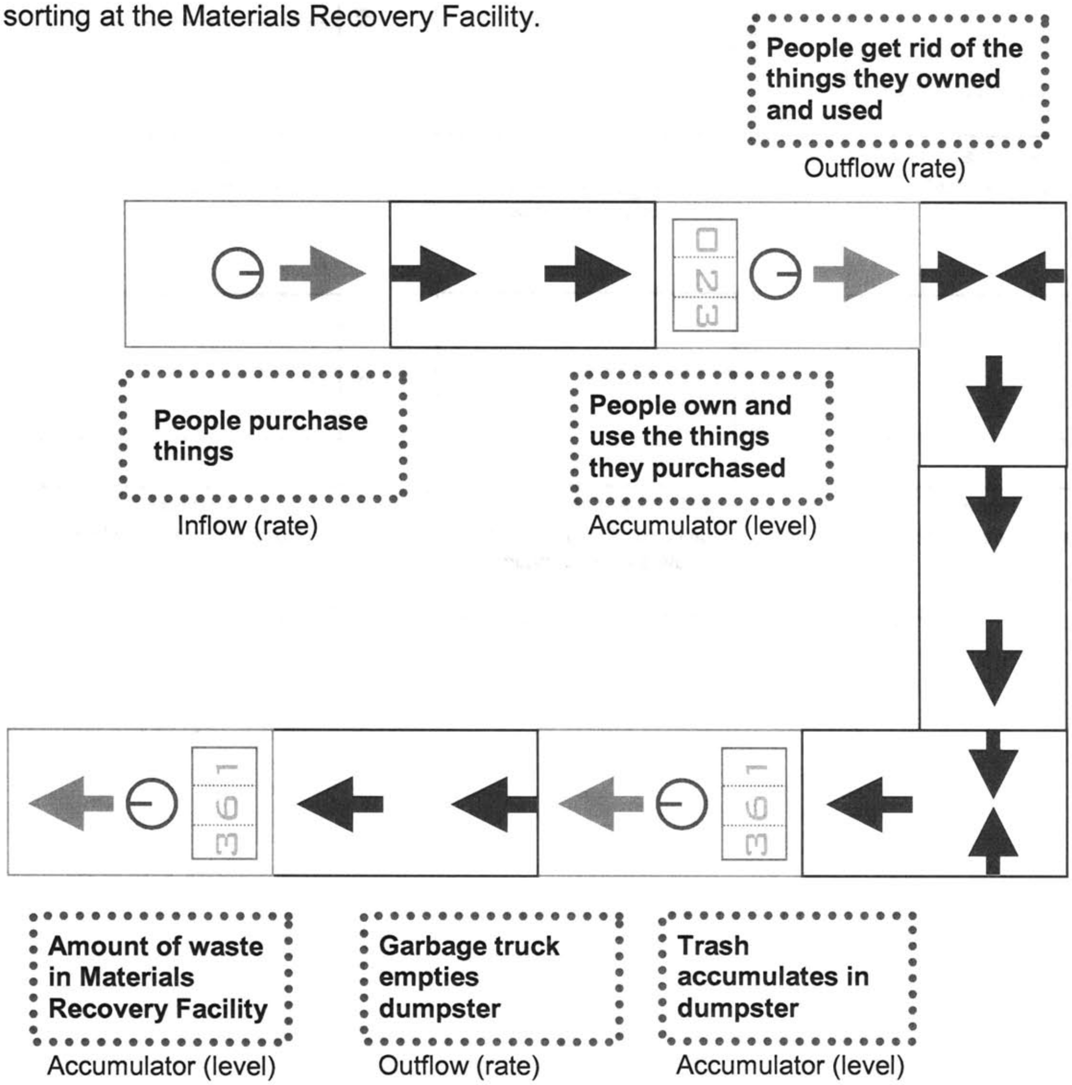


Figure 19: FUM3 simulation of a 3-accumulator open chain; Analogy using the "trash consequences" example.

Flowness Universal Model 4 : Probabilistic Distribution

Concepts introduced: ***Probability, Distribution***

Short description: one chain is connected to more than one chain, so material is distributed from one chain to the next chains in a probabilistic way. Distribution options are: 100% left, 75% left / 25% right, 50% left / 50% right, 25% left / 75% right, 100% right.

Thematic example: Garbage truck carries garbage to waste sorting at the Materials Recovery Facility; garbage accumulates in Materials Recovery Facility (MRF); Materials are sorted: 25% recyclable material, 75% waste; Recyclable material is transported to recycling facility; Waste is transported to landfill.

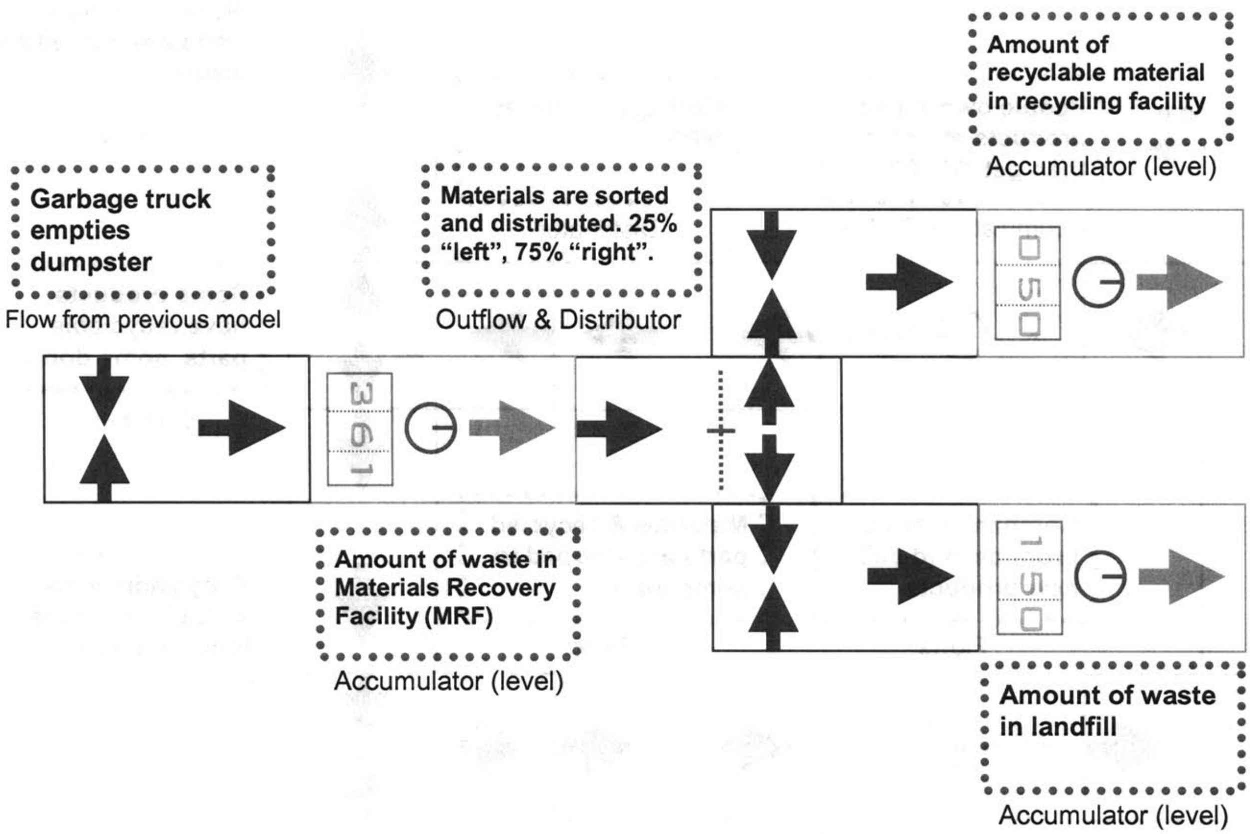


Figure 20: FUM4 simulation of a "1-to-2 accumulators" probabilistic distribution chain; Analogy using the "trash consequences" example.

Flowness Universal Model 5 : Closed Chain

Concepts introduced: ***Closed Chain, Closed Cycles,*** **Conservation of Matter,** ***Recycling / Downcycling***

Short description: several Accumulators connected as a cyclic chain, Outflow of one Accumulator serves as the Inflow of the next. Inflow to the "first" accumulator is external to the cycle and usually used only for initializing a model. A cradle-to-cradle system.

Thematic example: simplification of recyclable material chain: people purchase products, produce waste, recyclable parts are re-used by companies for lower-quality parts until they become waste as well (downcycling).

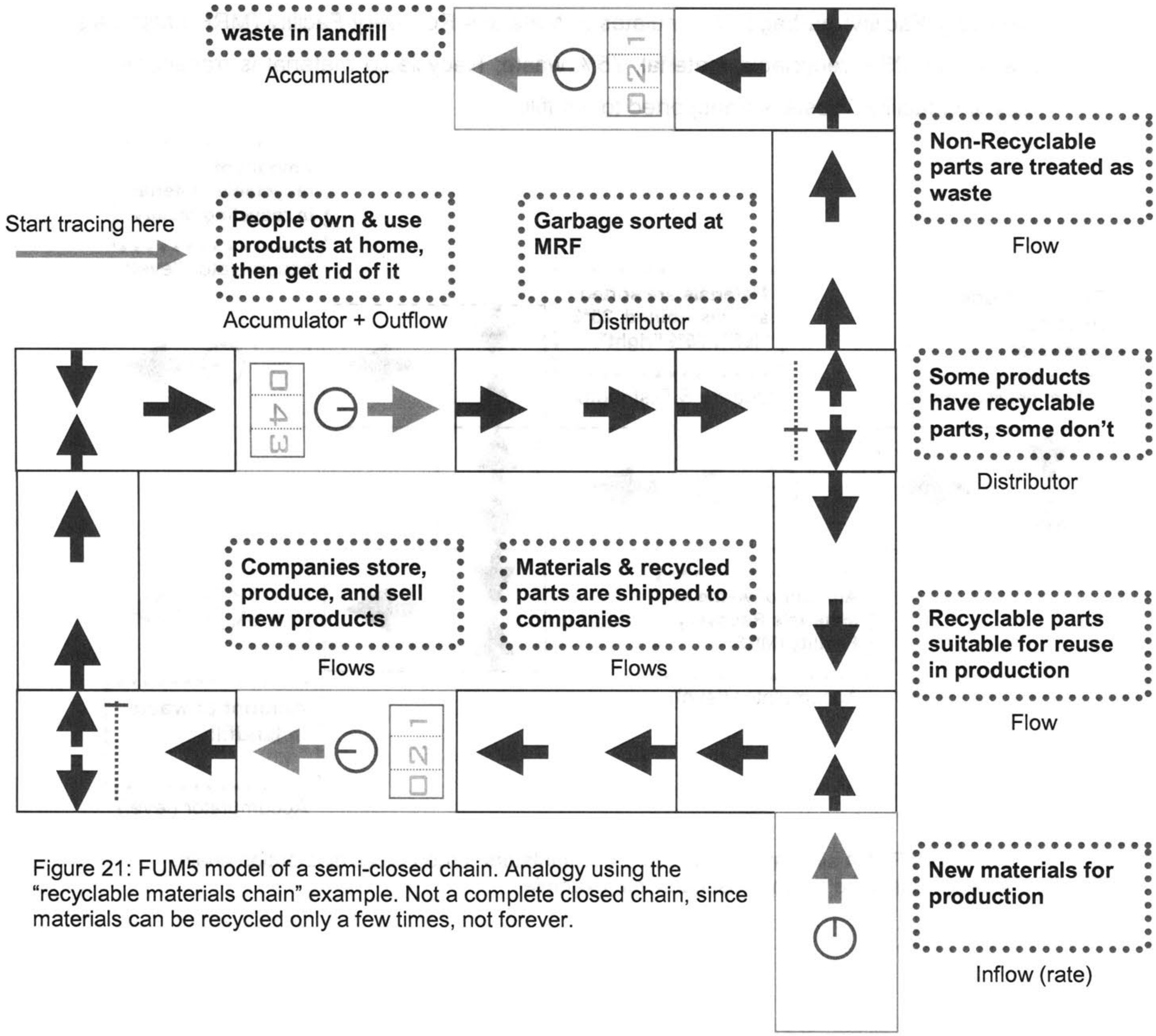


Figure 21: FUM5 model of a semi-closed chain. Analogy using the "recyclable materials chain" example. Not a complete closed chain, since materials can be recycled only a few times, not forever.

The Water Cycle is a good example for a complete closed chain where material is being conserved.

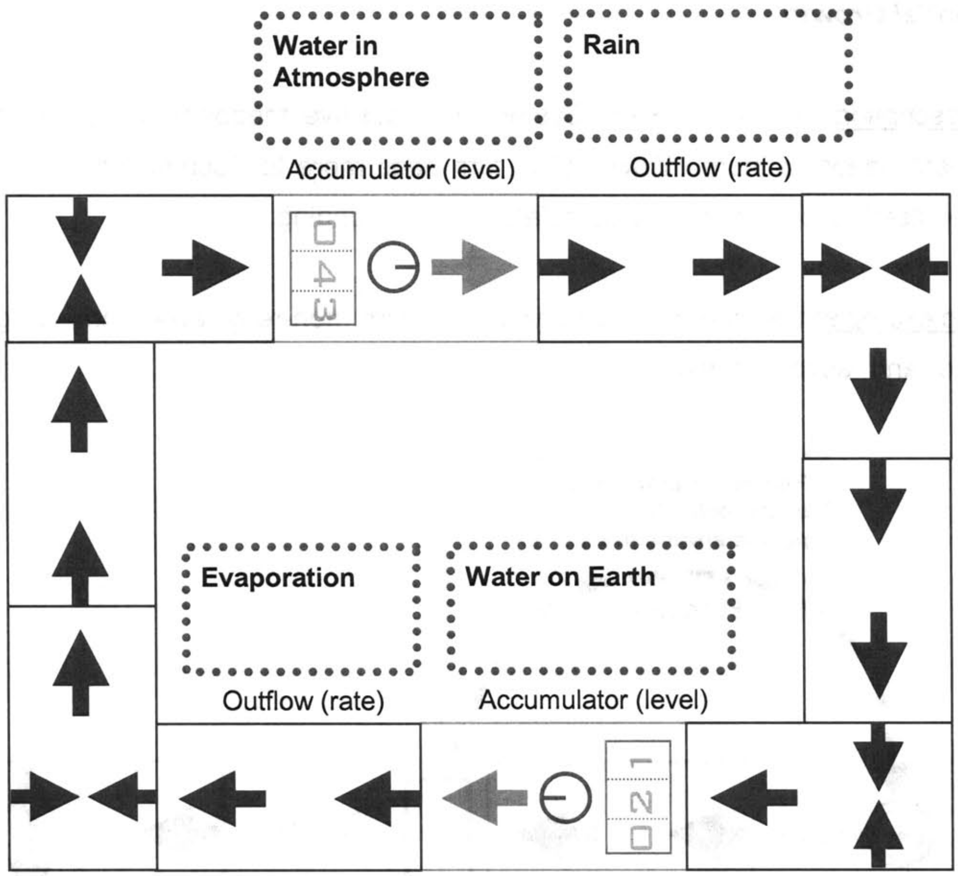


Figure 22: FUM5 model of a closed chain, analogy using the water cycle, a closed chain where material is conserved

Flowness Universal Model 6 : Feedback Influence - self reinforcement

Concepts introduced: ***Information Flow vs. Material Flow, More-is-More connection, Feedback, Positive Feedback, Loop-based Thinking, Reinforcing behavior, Exponential Growth.***

Short description: one Basic Flow System with positive feedback influence; more in Accumulator leads to more Inflow that in turn adds more to Accumulator. The system reinforces itself, and amount in Accumulator is compounding.

Thematic example: the more people recycle, the more "non-recyclables" are going to join the "trend" and recycle as well.

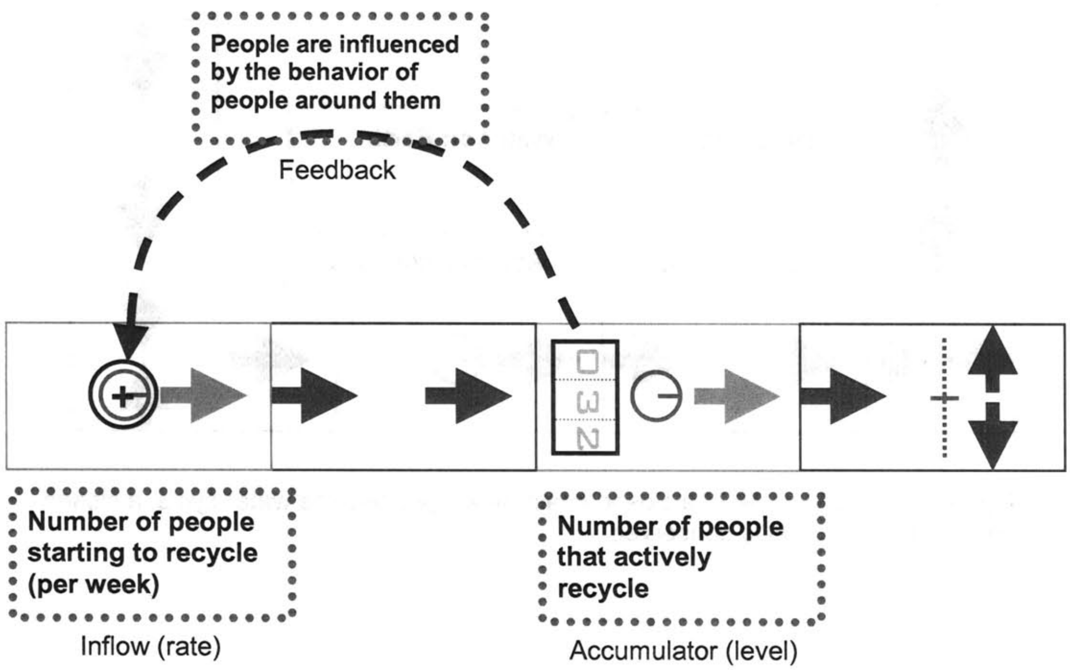


Figure 23: FUM6 model of a self reinforcing system. Analogy using the positive feedback pattern in people willingness to recycle; The number of people already actively recycling will influence more people to join and start recycling as well, which in turn will increase the number of people actively recycling. So the system is reinforcing itself.

Flowness Universal Model 7 : Feedback Influence - self regulation

Concepts introduced: ***Negative Feedback, More-is-Less connection, Regulating behavior.***

Short description: one Basic Flow System with negative feedback influence; more in Accumulator leads to less Inflow that in turn adds less to Accumulator. The system regulates itself, and the amount added to the Accumulator is gradually decreasing.

Thematic example: When we have plenty of stuff we care less about each item and are more likely to get rid of old or less useful things. If we have very little stuff, we will care more about each item and will try to use it for a longer period, fix it etc., and get rid of less stuff.

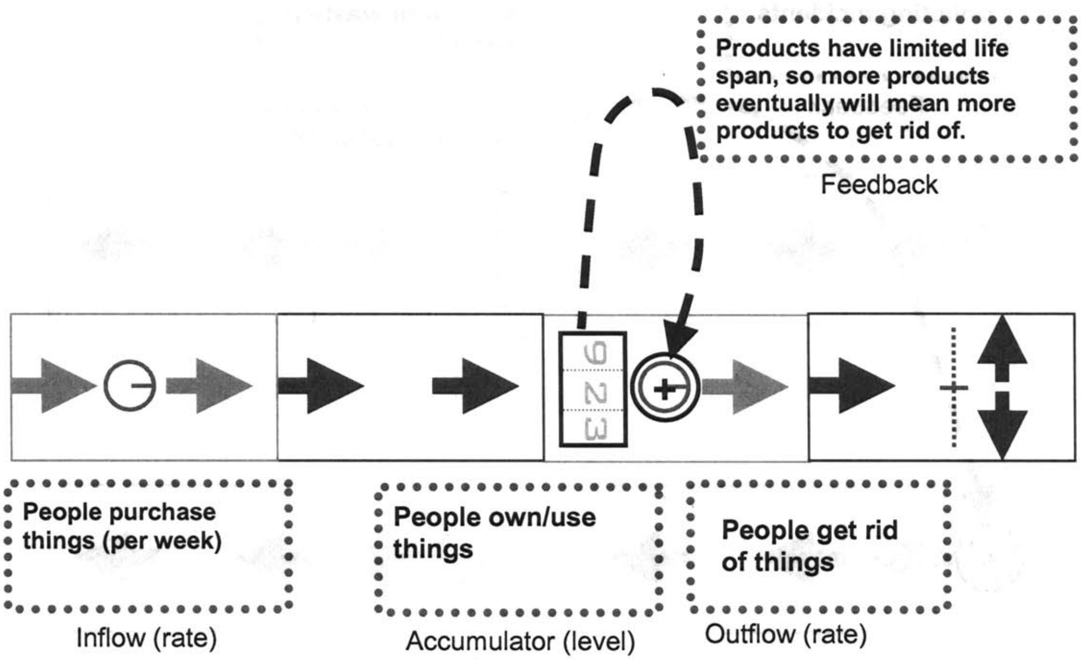


Figure 24: FUM7 model of a self regulating system. More in the Accumulator leads to more Outflow out from the Accumulator; Less in the Accumulator leads to less out from the Accumulator. Analogy using the inherent negative feedback pattern in physical stuff people own. Most physical products have a limited life span, so the more products one owns, there will be more products to get rid of. Also, the more stuff people own, the more space needed to store it and therefore people would be more likely to get rid of things. In the same way, the more people own, the less they care about each individual item they have, and are more likely to get rid of things.

Flowness Universal Model 8 : Feedback Influence - remote reinforcement

Concepts introduced: ***Interconnected Systems, one-way influence***

Short description: two Basic Flow Systems connected by a one-way positive influence; more in one Accumulator leads to increased Inflow into the other Accumulator, so in turn increased level in the other Accumulator. More in one BFS leads to more in another BFS.

Thematic example: as the amount of Waste in a certain landfill increases, it increases the potential pollution of the local environment (dust, odor, noise, groundwater contamination).

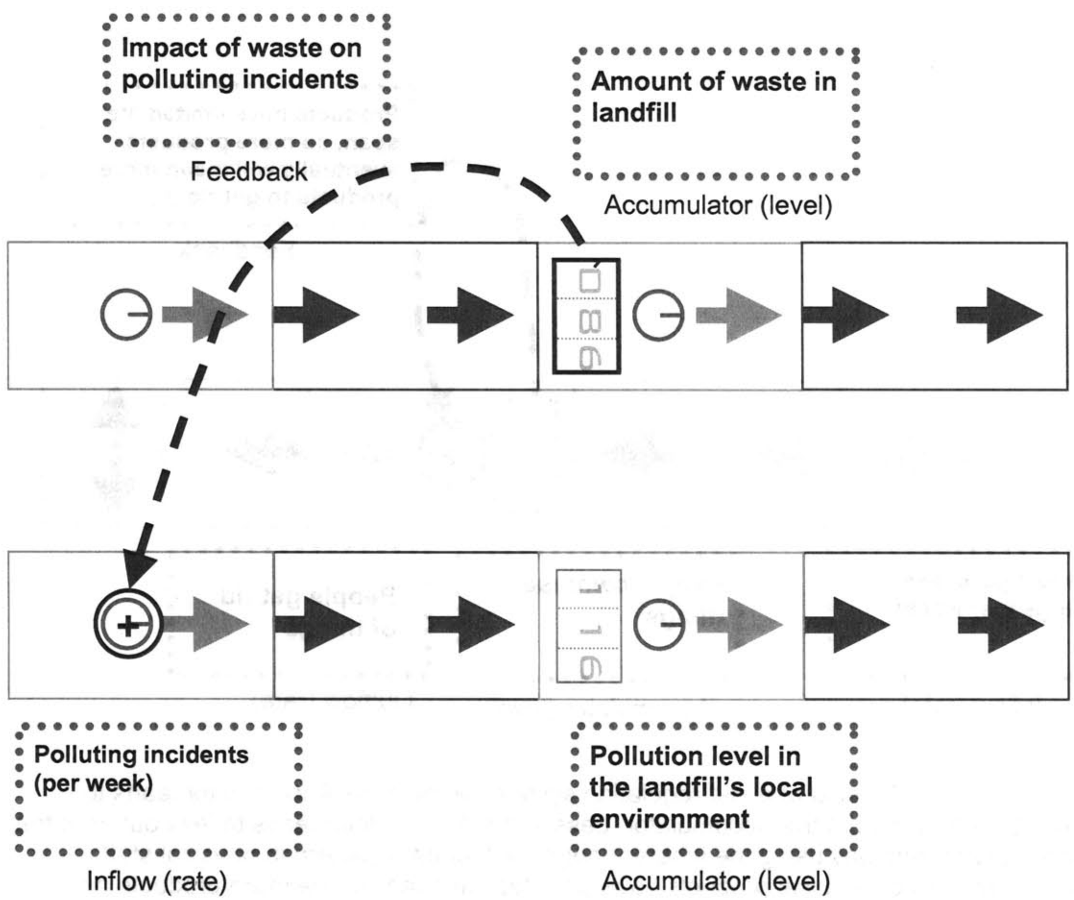


Figure 25: FUM8 model of a remote reinforcement system. More in one BFS leads to more in another BFS. Analogy using the impact amount of waste in a landfill has on the chance for polluting incidents, such as water contamination, air contamination (odor, dust), noise pollution etc.

Flowness Universal Model 9 : Feedback Influence - remote regulation

Concepts introduced: ***Interconnected Systems, one-way influence***

Short description: two Basic Flow Systems connected by a one-way positive influence; more in one Accumulator leads to increased Outflow out from the other Accumulator. So More in one BFS leads to less in another BFS.

Thematic example: as the amount of Waste in a certain landfill increases, it decreases the real estate values in the local towns & villages.

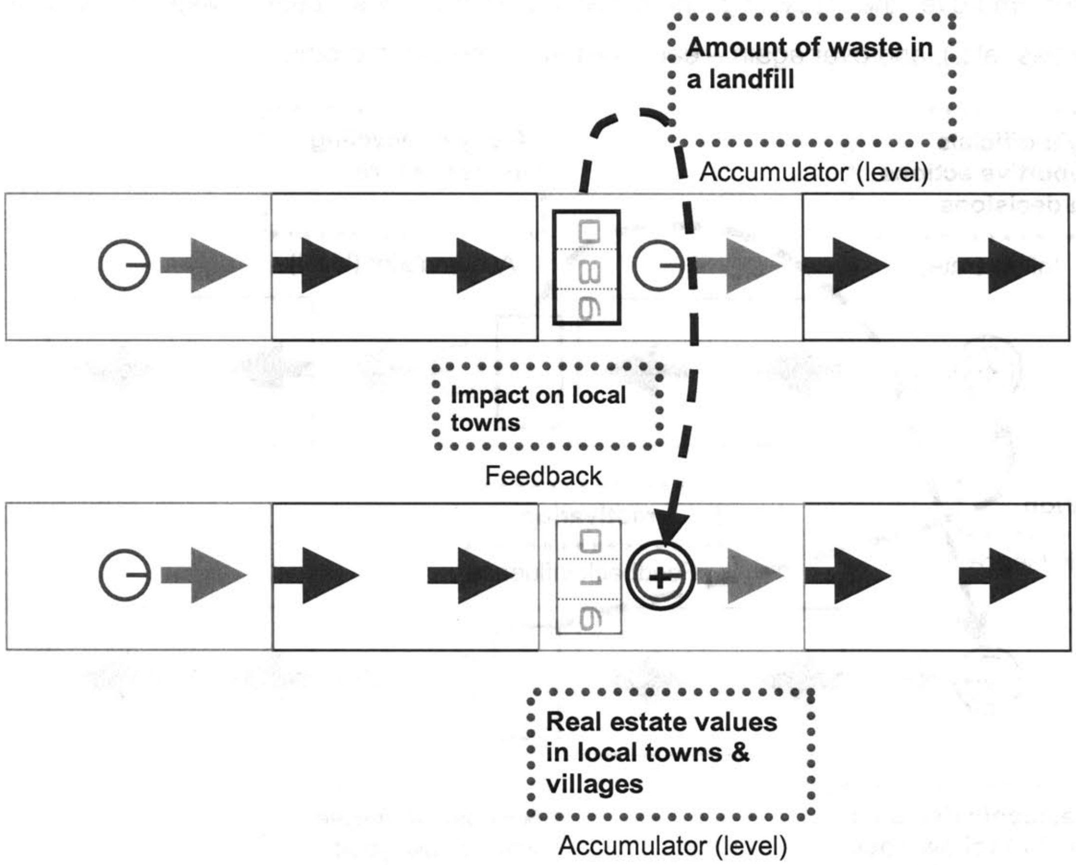


Figure 26: FUM9 model of a remote regulation system. More in one BFS leads to less in another BFS. Analogy using the impact amount of waste in a landfill has on the local towns & villages: The amount of waste in a landfill "regulates" the local town's real-estate market values…

Flowness Universal Model 10 : Feedback Influence - mutual reinforcement

Concepts introduced: ***Interconnected Systems, two-way influence***

Short description: Two BFS with two-way positive feedback influences; more in one Accumulator leads to more in the Inflow of the other Accumulator, and more in the other Accumulator leads back to more in the Inflow of the first Accumulator. So more in one BFS leads to more in the other BFS, which leads to more in the first BFS and back again.

Thematic example: as a city's recycling infrastructure improves (more special bins, orderly collection, clear recycling instructions etc.), more people follow good recycling habits, which will motivate city's officials (through direct and indirect communication) to further improve the recycling infrastructure (more bins, better Material Recovery Facilities, etc.), and over again – each system reinforces the other.

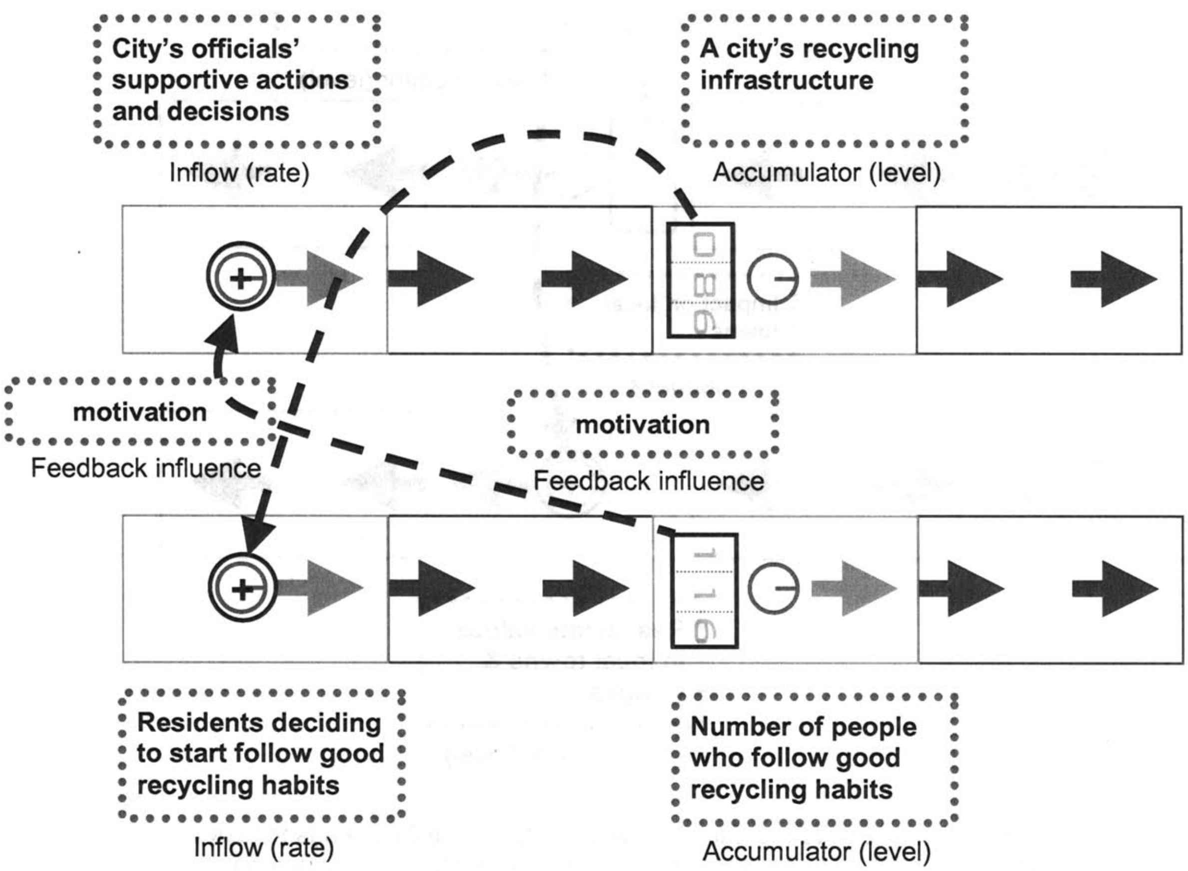


Figure 27: FUM10 model of a mutual reinforcement system. More in one BFS leads to more in another BFS which in turn leads to more in the first BFS. Analogy using the influence a city's recycling infrastructure has on resident's motivation to recycle, and residents recycling habits influence on city's officials' motivation to improve city's recycling infrastructure.

Flowness Universal Model 11: Feedback Influence - mutual reinforcement & regulation

Concepts introduced: ***Oscillation***

Short description: Two BFS with one-way positive & one-way negative feedback influences; more in one Accumulator leads to more in the Inflow of the other Accumulator, and more in the other Accumulator leads back to more in the Outflow of the first Accumulator. So more leads to more, which in turn leads to less.

Thematic example: the attractiveness of a certain landfill oscillates based on the balance between the landfill's infrastructure and the landfill active usage. As attractiveness increases (from investment in infrastructure) more trucks will choose this landfill. After some time, the landfill will be overloaded with trucks coming, and the infrastructure will not support the demand. Then site attractiveness will decrease, and trucks will start choosing other sites. Then, demand/usage will decrease and attractiveness will increase again. If demand (Outflow – trucks using landfill) surpass capacity (Inflow – investment in infrastructure) attractiveness decreases; if capacity surpass demand attractiveness increases.

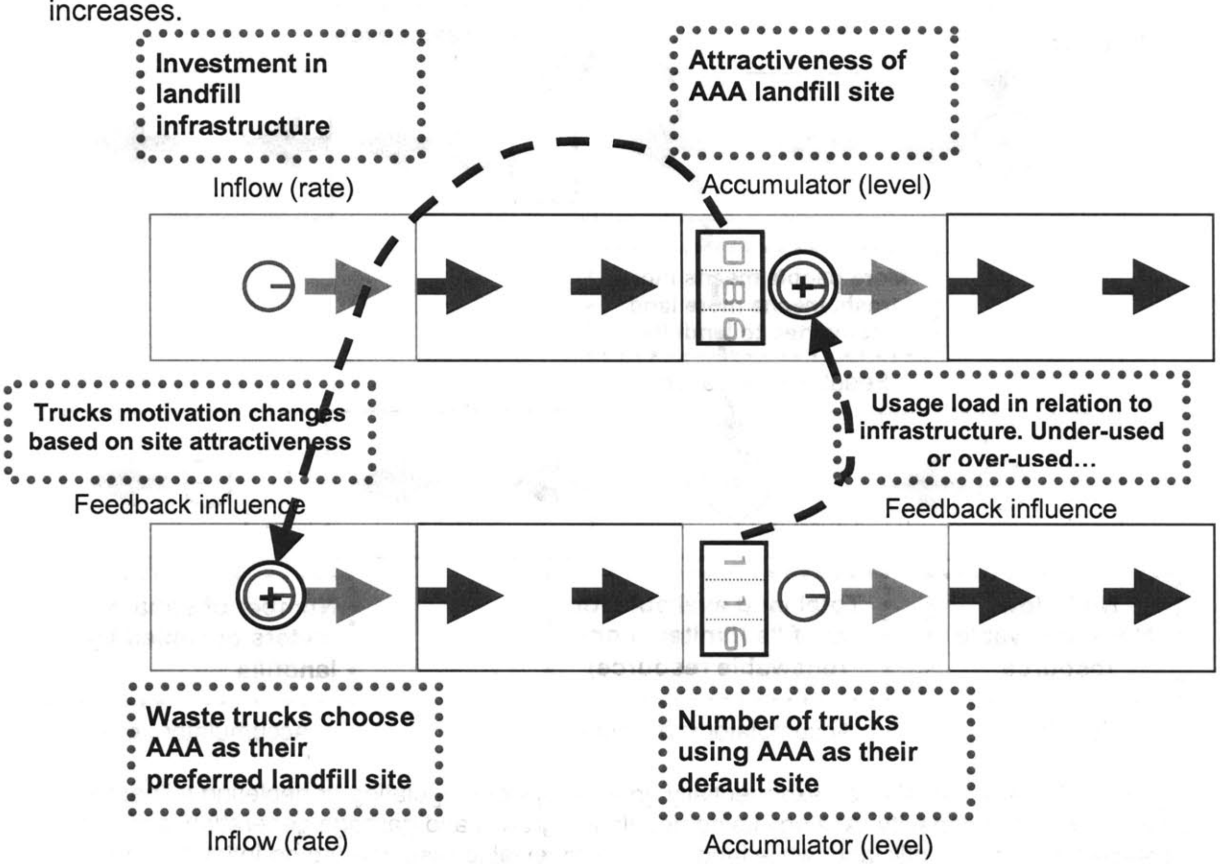


Figure 28: FUM11 model of an oscillating social system as a result of mutual positive and negative feedback loops. The more attractive a landfill is, the more trucks will go there (demand), which in turn will decrease attractiveness, which in turn will decrease demand, which in turn will increase attractiveness.

Flowness Universal Model 12 : Resource Depletion

Concepts introduced: ***Resource Depletion, Exponential vs. Linear, Merging FUMs together to construct larger more complex simulations.***

Short description: two FUMs merged, FUM6 + FUM9. The result is an exponential-growth system depletes linear-growth system. This FUM is an example for using the FUMs as building blocks to create new common patterns.

Thematic example: population growth increases exponentially. More people means more garbage generation. More garbage means more land needed for landfills. But, land capacity is a limited, non-renewable resource (the earth land is limited). So an exponential growth system regulates or depletes a limited capacity.

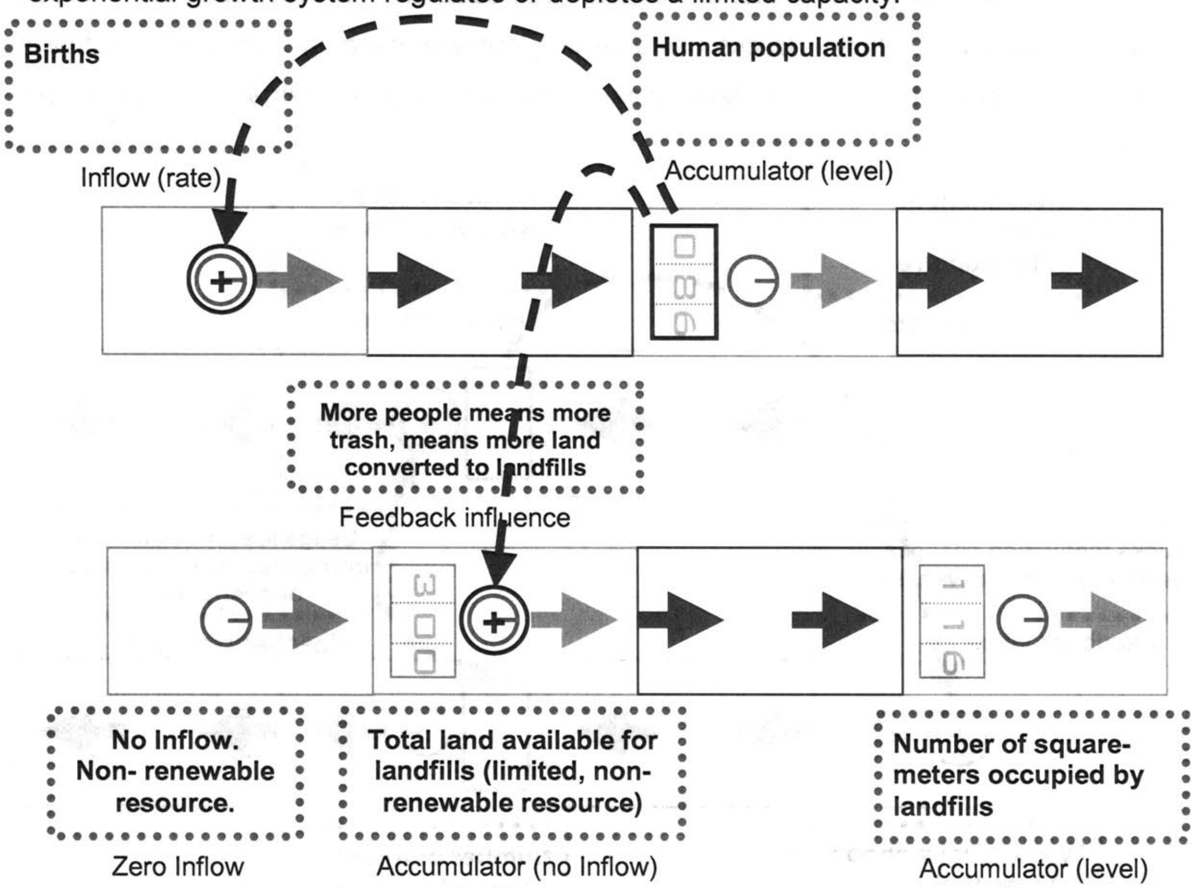


Figure 29: FUM12 model of an exponentially growing system regulating or depleting a linearly-growing or limited capacity. Analogy using population growth and garbage generation, and the increased need for landfill land, while land is a non-renewable resource (so no Inflow). Other examples are all the natural resources human consume, including wood, metals, oil, air, water etc. Some of this resources have an Inflow (wood from trees) while others don't (water is a closed system with fixed quantity, oil take million of years to re-generate).

CHAPTER 5. DESIGNING FLOWBLOCKS: A NEW LEARNING TECHNOLOGY

Throughout human history, people learned by interacting with their physical environment. Children played with rocks and sticks, water and sand, experimented with different materials, and in a gradual process reached conclusions about the world around them. Learning Objects or Manipulatives are sets of physical objects intentionally designed to promote hands-on learning experiences, for example the Unit Blocks, Cuisenaire Rods, or Pattern Blocks.

In this chapter I present a detailed description of my design inspiration, design process and technical implementation.

> I start with the Learning Objects designed by Friedrich Froebel and Maria Montessori, and the new classification I developed based on the commonalities and differences in their designs. I show how this classification is valid for classic as well as modern toys, in a range of domains. I end this section by laying out the design principles behind Froebel's and Montessori's designs, as reflected from their artifacts.
>
> I continue and present FlowBlocks, the physical learning technology I designed & implemented on top of the Flowness modeling language. I explain the careful design choices I made in the physical design, and lay the five design principles that guided my conceptual design. FlowBlocks conceptual design is a unique combination of Froebel's and Montessori's principles: a "computational construction kit" focused on "conceptual manipulation".
>
> I end with the technical implementation, detailing the hardware design.

A New Classification of Toys and Learning Objects

Traditional toys, and especially traditional Learning Objects can be great inspiration for designers of new learning technologies. The traditional Learning Objects have been actively used for over a century in kindergartens and classrooms to help children learn in the process of play. Two designers of traditional Learning Objects stand out as the pioneers of the field: Friedrich

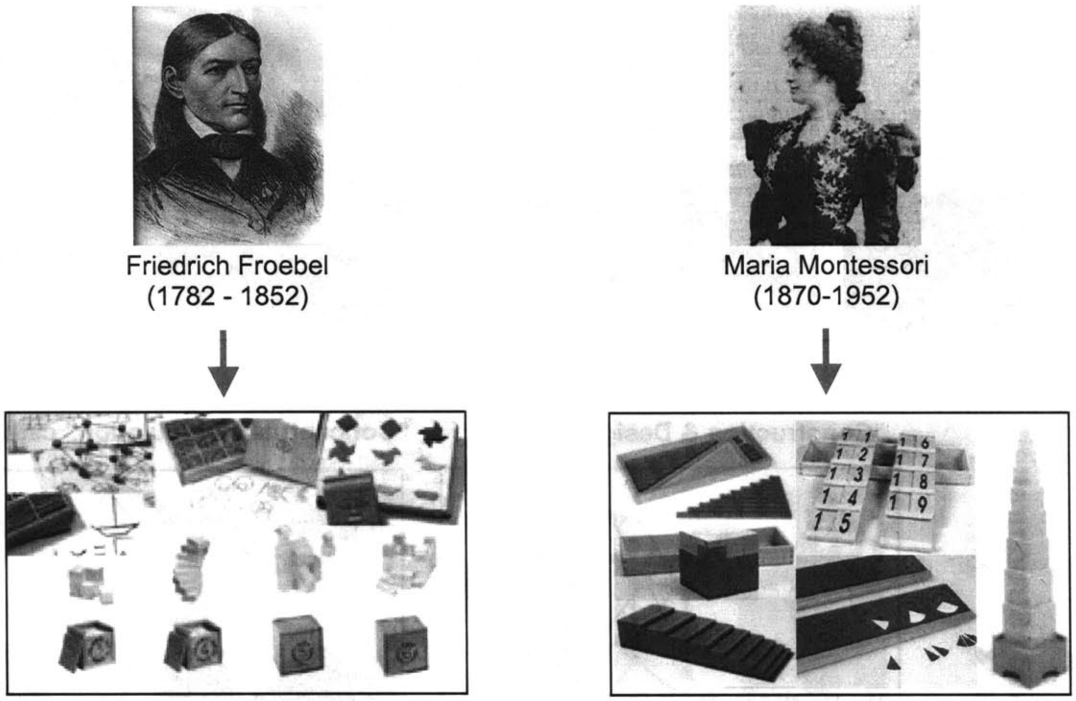
Froebel and Maria Montessori, the great manipulatives designers of the 19th and 20th centuries.

In the background chapter of this thesis I presented in detail the origins and history of Learning Objects, and argued that Friedrich Froebel and Maria Montessori represent two distinct "schools of thought" with regards to the design of Learning Objects (see page 19). I classified their Learning Objects into two distinct categories: I termed Froebel's objects "Construction & Design" Learning Objects, and Montessori's "Conceptual Manipulation" Learning Objects.

The "Construction & Design" category includes construction kits that enable spatial modeling of 2D and 3D structures, promoting the creation of models that are visually or structurally similar to real-life structures (like building, vehicles, trees etc.).

The "Conceptual Manipulation" category includes modular sets of objects that are intentionally designed to surface specific abstract concepts, promoting hands-on manipulation without encouraging formation of models that are visually similar to real-life structures.

Clearly, in the hands of a good teacher or an "abstract-thinker" child, Froebel's Learning Objects can be used to surface abstract concepts. In the same way, an engineer-minded child can use Montessori's materials to create models that are structurally similar to real-life models. But, the way the objects are designed promotes a certain activity; the "center of gravity" of each design in the separate categories is clearly different: Froebel's designs promote construction & design, while Montessori's designs promote conceptual manipulation.



Froebel designs: Defining a **"Construction & Design"** Learning Objects category

Montessori's designs: Defining a **"Conceptual Manipulation"** Learning Objects category

Figure 30: The "Construction & Design" vs. "Conceptual Manipulation" classification of Learning Objects, derived from the difference in the design styles of Friedrich Froebel and Maria Montessori.

This new classification and its two respective categories exist beyond the objects designed by Froebel and Montessori, in the Learning Objects, toys, construction kits, and educational manipulatives that are popular today in homes and classrooms.

In the next diagram I map popular toys, educational manipulatives, digital toys, and educational technology research projects into the two categories, showing how the "Construction & Design" vs. "Conceptual Manipulation" classification of Learning Objects is valid for classic as well as modern toys, and across different conceptual domains including the structural, temporal, and computational domains.

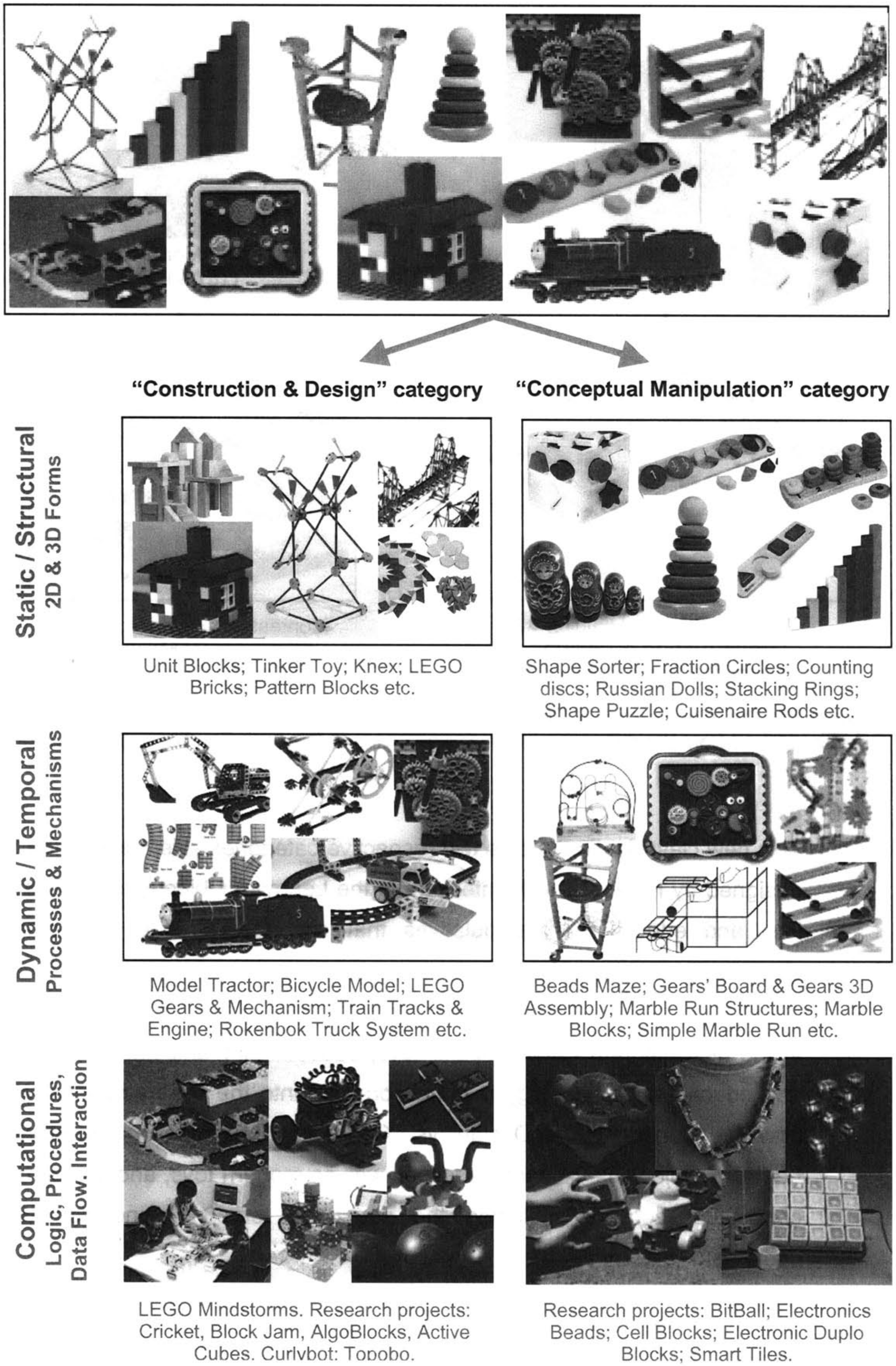


Figure 31: The "Construction & Design" vs. "Conceptual Manipulation" classification presented across the structural, temporal, and computational domains.

The Static/Structural domain

"Construction & Design" toys in this domain include Unit Blocks, Tinker Toy, Knex, and LEGO Bricks - all enabling modeling of houses, bridges, castles, vehicles, figures etc. The Pattern Blocks are another member of this category. Although Pattern Blocks directly represent abstract concepts from geometry, they are usually used to model 2D forms that are visually similar to real-life forms, such as flowers, figures, houses etc.

"Conceptual Manipulation" toys in this domain include Shapes Sorter and Shapes Puzzle that enable gradual assimilation of the "geometrical shape" concept and identification of the different shapes; Stacking Rings that enable gradual assimilation of the "diameter" concept; Russian Dolls for the "volume" concept; Cuisenaire Rods for the "number" concept; Counting discs for counting; and Fraction Circles for the "fractions" concept. Clearly, these toys do not promote modeling of structures that are visually similar to real-life structures, but rather focus on gradual assimilation of a specific abstract concept.

The Dynamic/Temporal domain

"Construction & Design" toys in this domain include a LEGO Technic Model Tractor and a K'nex Simple Machine Bicycle Model, both enabling creation of dynamic mechanisms in models that are visually and structurally similar to real-life machines. A model train tracks & train engine that enable exploration of motion and processes in a system that is visually similar to real-life train. And a Rokenbok system that enables exploration of dynamic supply with a remote control truck in a factory-like environment.

"Conceptual Manipulation" toys in this domain include a Beads Maze, enabling young minds to explore directed movement with no real-life analogous (compare with pushing a wooden train along a curved truck); The gears board & 3D gears assembly systems, both enabling construction of mechanisms with non real-life analogies (compare with the LEGO gears, LEGO Tractor and the K'nex bicycle); and three types of marble run systems, all enabling exploration of concepts such as motion, dynamic processes, and cause-and-effect in a system that is not visually similar to and real-life system (compare with the train truck and the Rokenbok system).

The computational domain

"Construction & Design" prototypes in this domain include the LEGO Mindstorms robotics creation system and MIT Media Lab's Cricket invention kit (Resnick 1996), both enabling construction and programming of computational robots and interactive design projects; Sony's Block Jam prototype (Newton-Dunn et al. 2003) that enables creation of electronics music; Suzuki and Kato's AlgoBlocks (Suzuki and Kato 1995) that enables creation of computer programs using the LOGO language; Osaka's university's Active Cubes (Ichida et al. 2004) that enables formation of 3D models with sensors and actuators; and MIT Media Lab's Curlybot (Frei et al. 2000) for 2D motion recording, as well as Topobo (Raffle 2004) for the construction of 3D biomorphic forms with kinetic memory.

"Conceptual Manipulation" prototypes in this domain include MIT Media Lab's BitBall (Resnick 1998) for exploration of the "velocity/acceleration" concept and Electronics Beads (Resnick 1998) for exploration of the "dynamic processes" concept, respectively; University of Colorado's Smart Tiles (Elumeze 2005) and Boda Blocks (Buechley 2007) for exploration of the "cellular automata" language and the "emergent behavior" concept; and Peta Wyeth's Electronic Duplo Blocks prototype (Wyeth, 2001) for the exploration of basic concepts in logic such as "AND", "NOT, "OR" etc.

As we can see from this analysis, the "Construction & Design" vs. "Conceptual Manipulation" classification is valid beyond Froebel's and Montessori's designs, and is very relevant to designers of toys, learning technologies, and cutting-edge research projects aimed at children and learning.

In the following section I lay out the similarities and differences in the design principles reflected from Froebel's and Montessori's designs, as an introduction to my design of FlowBlocks.

The Design Principles behind Froebel's and Montessori's Learning Objects

Comparing and contrasting the Learning Objects designed by Froebel and Montessori helped me understand the similarities and differences in their designs. Figure 32 below lays out my view of their "design principles" as reflected from their artifacts.

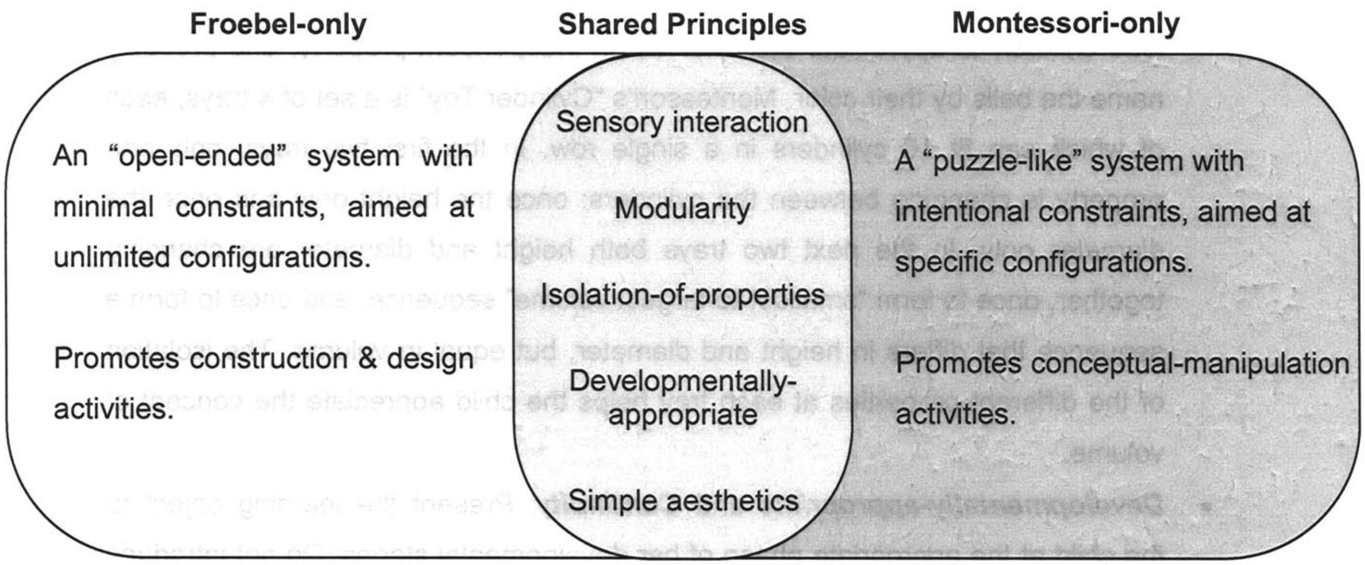


Figure 32: Similarities and differences in the design principles of Froebel and Montessori

Froebel - Montessori shared design principles

- ***Sensory interaction***: Let the sensory interaction lead the cognitive development. Sensory means especially touch, but in some cases also sound (e.g. Montessori's bells). This principle is probably a result of the "learning from experience" movement traced back to John Locke's revolutionary educational ideas in the 17^{th} century, specifically the notion that knowledge comes from experience and experiment: "All ideas come from sensation or reflection" (Locke 1698).
- ***Modularity***: Create sets of modular artifacts that enable active interaction, exploration, and experimentation. The modularity promotes independent or group interaction, allowing children to figure things out on their own. For example, Froebel's gift number 3 is a modular set of 1" wooden cubes, enabling modeling and exploration of 3D spatial structures. Montessori's "long stairs" are a modular set of 10 wooden bars, varying in length from 10cm to 100cm in 10cm steps, enabling exploration of the "integer number" concept.

- ***Isolation-of-properties***: Separate the "variables" for the child, so interaction with the artifact highlights one property or one concept and helps the child to notice/experience the essence. For example, Froebel's "gift number 1", the wool balls, is a set of six identical soft balls with one difference only: their color. The interaction with the balls has many learning opportunities (explore movement, shape, manipulation, gravity), but the isolation of the color property will over time lead children to appreciate the color as an independent property, and probably name the balls by their color. Montessori's "Cylinder Toy" is a set of 4 trays, each of which can fit 10 cylinders in a single row. In the first two trays, only one property is changing between the cylinders: once the height only and once the diameter only. In the next two trays both height and diameter are changing together, once to form "smallest-to-largest volume" sequence, and once to form a sequence that differs in height and diameter, but equal in volume. The isolation of the different properties at each tray helps the child appreciate the concept of volume.
- ***Developmentally-appropriate*** and ***Continuity***: Present the learning object to the child at the appropriate phase of her developmental stages. Do not introduce advanced concepts too early, and let the child dictate the rate of progress. The Learning Objects should support continuity in the child's learning process; so one object should build upon the learning/skills acquired from interacting with a previous object. For example, Froebel gifts were introduced in a sequence, at specific ages, starting with the wool balls at 3-6 months old.
- ***Simple aesthetics***: Use simple objects, aesthetically pleasing to the children. The visual design should be aligned with the conceptual design, so color and shape should serve the concept, and there should not be any unnecessary decorations that can add new properties beyond the conceptual design. For example, Montessori's "pink tower" is colorful and aesthetically pleasing for children, the pink color is identical for all cubes and therefore do not compromise the "isolation of properties" principle. In this object the changing property is the cube's size, there are 10 cubes, varying in size by one cubic centimeter from large to small, enabling children to build tall stable towers.

Froebel - only design principles:

1. ***Physical language, aimed at many configurations***: Froebel's Learning Objects are an open-ended physical language, enabling children to form many different configurations. The design does guide towards specific configurations, and the child might create configurations that have never been created before or have not been anticipated by the designer.
2. ***Focus on construction & design***: Froebel's Learning Objects are aimed at spatial modeling, enabling children to design 2D and 3D structures. The structures created with Froebel's objects are usually visual models of real-life, such as train, house, flower, and boat; or are visual patterns that are abstract yet aesthetically pleasing. Froebel's objects can support learning of abstract concepts such as arithmetic, counting, fractions, and geometry, but requires scaffolding by a specific activity or a trained person.

Montessori - only design principles:

1. ***Physical "puzzle", aimed at specific configurations***: Montessori's Learning Objects are designed to guide the child towards specific "successful" configuration ("self-correcting"), like a puzzle more than a language.
2. ***Focus on conceptual manipulation:*** Montessori's Learning Objects are aimed at surfacing a specific abstract concept trough hands-on manipulation. The design does not promote visual modeling; it will be un-intuitive to use Montessori's objects to create structures that visually resemble real-life structures. Montessori's design serves one and only one aim: make a specific abstract concept more salient.

Designing FlowBlocks: a Physical Learning Technology

Inspired by the physical learning environments designed by Friedrich Froebel & Maria Montessori on one hand, and the digital-physical environments designed by Mitch Resnick & Hiroshi Ishii on the other hand, I implemented the Flowness modeling language as a digital learning object I call FlowBlocks.

FlowBlocks are physical blocks with embedded digital computation. The blocks snap together and pass sequences of lights from block to block, forming simulations of continuous flow.

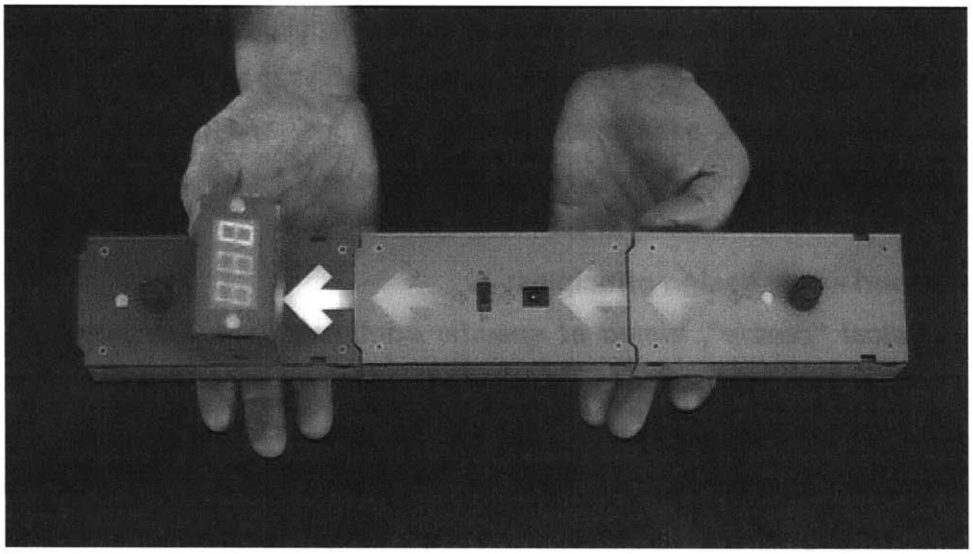
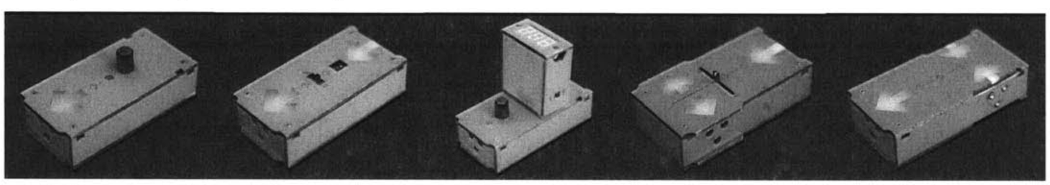


Figure 33: The FlowBlocks physical implementation; wood & electronics.

As a physical learning object, the FlowBlocks design followed the Froebel-Montessori shared design principles (see above), and introduced a unique hybrid of the Froebel-only and Montessori-only principles, creating a physical language that supports many configurations (Froebel) while promoting conceptual manipulation (Montessori).



Inflow **Straight** **Accumulator** **Distributor** **Turn**

Figure 34: The FlowBlocks individual blocks

As a digital environment, FlowBlocks was inspired by Resnick's work on Behavior Construction Kits (Resnick 1993) and Digital Manipulatives (Resnick 1998), and on Ishii's work on Tangible User Interfaces (Ishii and Ullmer 1997), interfaces that benefit from people's lifelong interaction with the physical world.

The Physical Design

The physical FlowBlocks collection was implemented as a set of wooden blocks, with embedded digital electronics in each block, and with magnetic connectors that snaps blocks together as well as transfer power and signal from block to block.

The physical FlowBlocks are an authentic implementation of the Flowness modeling language. Each of the FlowBlocks physical blocks can be directly mapped to the corresponding Flowness element, including the feedback connections.

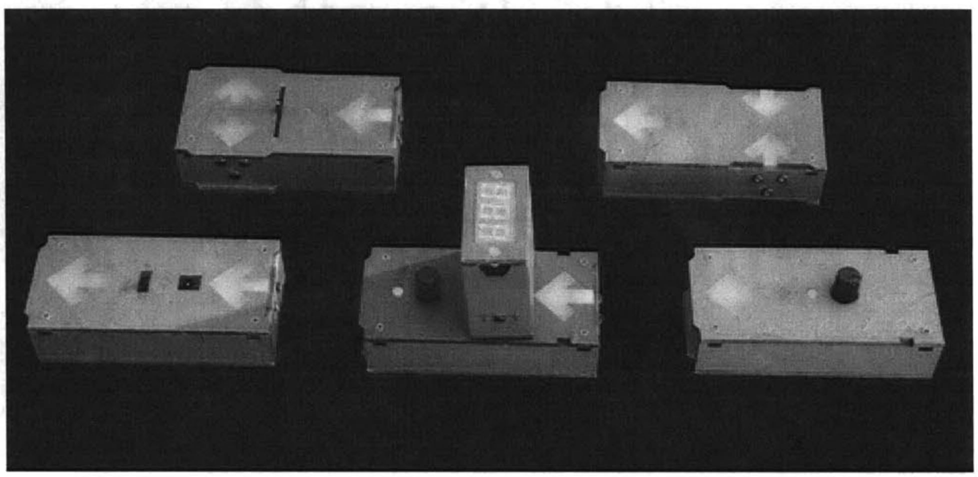


Figure 35: The FlowBlocks collection

The blocks were designed as rectangle boxes. Each block is 60mm x 120mm, so they fit comfortably in a child's hand, but are not too small to be used as a modeling material (see design principle 2 in the next section). Red superbright LEDs shine through the arrow-shape translucent "window", creating the illusion of moving light from block to block.

Each block has a dedicated microcontroller (see Figure 36) that manages incoming signal; outgoing signal; signal delay; LEDs blinking; user interaction through the dials; and the accumulator's numeric display. The 5V battery power is distributed from the straight block (which has 4 AAA batteries) to the rest of the blocks. Both power and signal are transferred through the custom-made magnetic connectors. The connectors have magnets on one end (the male end), and loose-screws on the other end (female end).

When a child brings two blocks close to each other, the magnets pull the screws, which in turn pull the block (see figure 37). The two blocks snap to each other, and the screws snap onto the magnets, creating a seamless conductive connection from screws-to-magnets, forming a connection between the PCBs in each of the block.

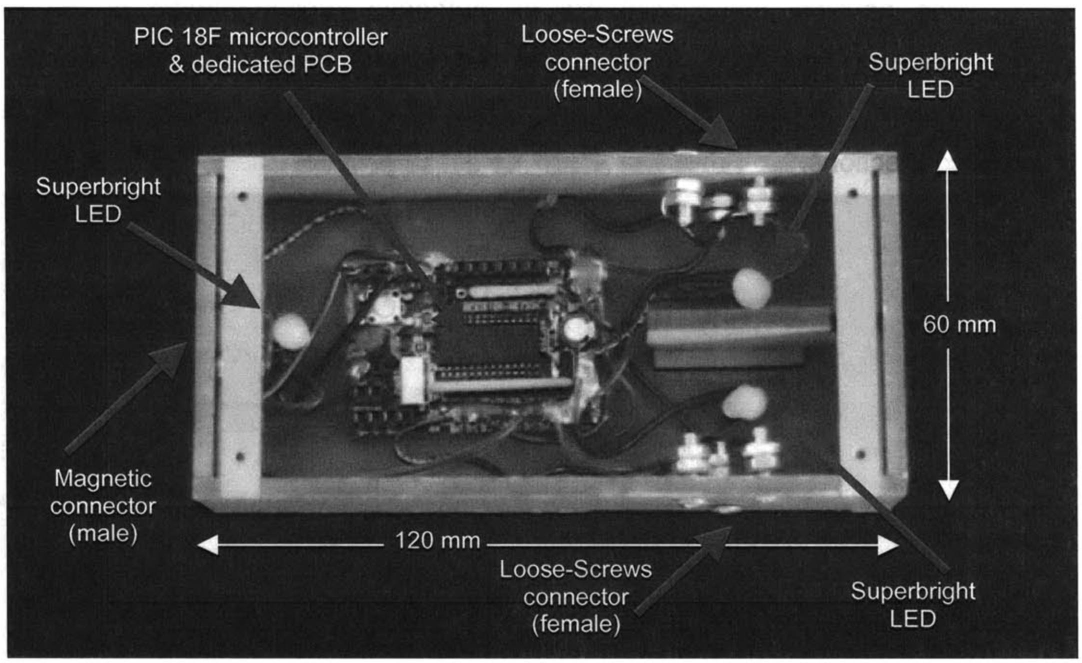
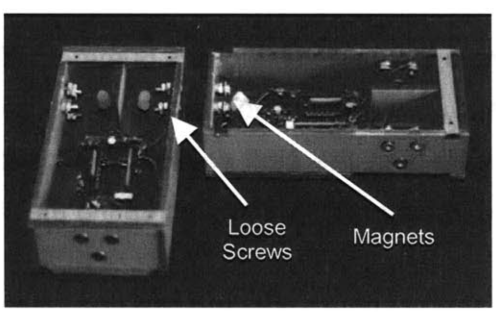


Figure 36: Inside the Turn FlowBlock



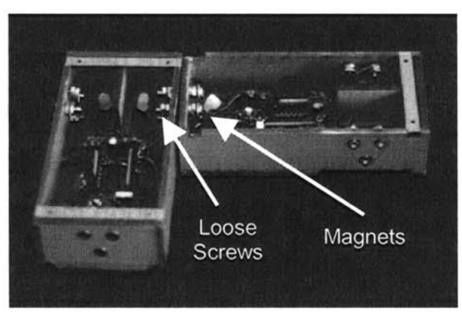


Figure 37: The magnetic connectors pull the block together, and form a seamless conductive connection between the magnets end and the loose-screws end.

The "straight-angle" design of the blocks & connectors enables only two types of connection: a straight connection (block after block) or a 90-degree angle connection (one block perpendicular to the next). This deliberate design decision encourages children to focus on the behavior-level rather than the geometry-level (see design principle 2 and 4).

For example, figure 38 shows a "closed chain" model with one accumulator. The lights move around in a closed cycle, entering the accumulator from the right and exiting the accumulator from the left. The number of lights in this model is conserved, no "material" is being lost. As a real-time hands-on simulation, this model is very intriguing for children, giving them a way to explore abstract dynamic behavior through play, without focusing on any real-life example.

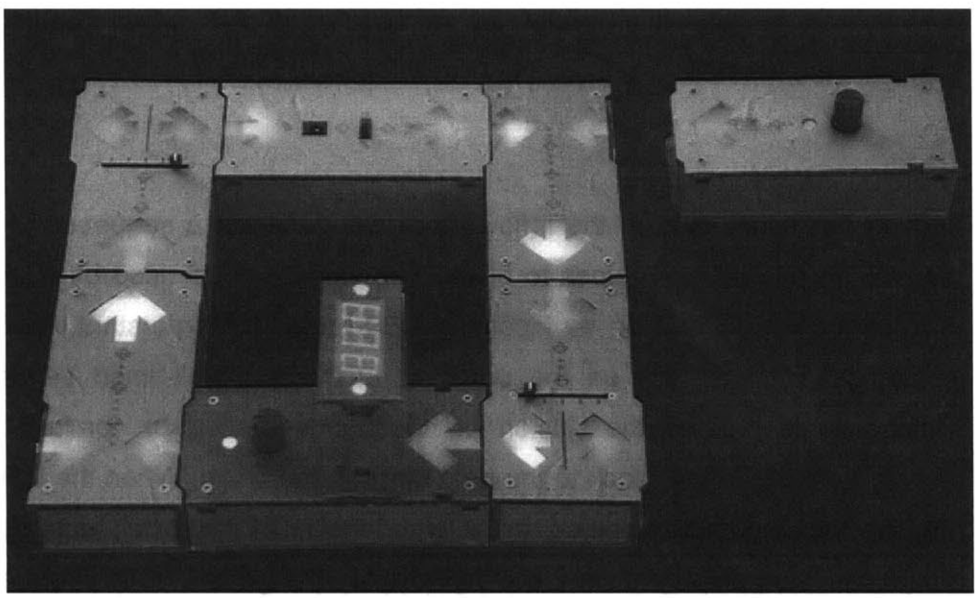


Figure 38: The "straight-angle" design limits the number of possible configuration, but enables discovery of structures that are meaningful on the behavior-level rather than the geometric-level (see Design Principles 2 and 4).

The arrows on each of the blocks are translucent acrylic "windows". The arrows inform the child about the behavior of each block and the underlying modeling language. When connected together, FlowBlocks arrows create a type of a "casual language", a "flow diagram", helping children predict the simulation's behavior before they actually start to simulate. Over time, the experienced user will be able to imagine simulations by arranging the blocks, without the actual simulation. With more complex models, even the experienced user will need to simulate in order to observe the unfolding system behavior.

Figure 39 shows the Basic Flow System, the fundamental dynamic system consisting of an Inflow block, Accumulator block, and an Outflow (build-into the Accumulator block). In the physical FlowBlocks, a battery block is essential, hence the Straight block. This Basic Flow System is a simple model of dynamic behavior, enabling children to experience continuous flow, rate-of-change, simultaneous processes, dynamic equilibrium, and more. In my workshops with children I saw that a play session of approximately one hour is usually enough for a 10-15 years-old child to assimilate the Basic Flow System, making it possible for children to use this model as a “building block” when forming more sophisticated models.

Turning the Inflow dial on the Inflow block will generate a sequence of signals that will be passed from block to block. The signal will be used by each of the microcontrollers to turn on its incoming LED, delay for an instant, turn off the incoming LED and turn on the outgoing LED. This well-timed sequence of blinking lights creates the illusion of continuous motion or continuous flow, moving from the Inflow block to the next block in the chain. When the light signal reaches the Accumulator block, the microcontroller in this block increments the numerical value displayed on the 3-digit display (range is 0-999). From a child’s perspective, the lights are flowing into the accumulator, filling it up with “light units”. When the Outflow dial is turned on, a sequence of lights is starting to flow out from the Accumulator, decrementing the numerical value displayed on the 3-digit display.

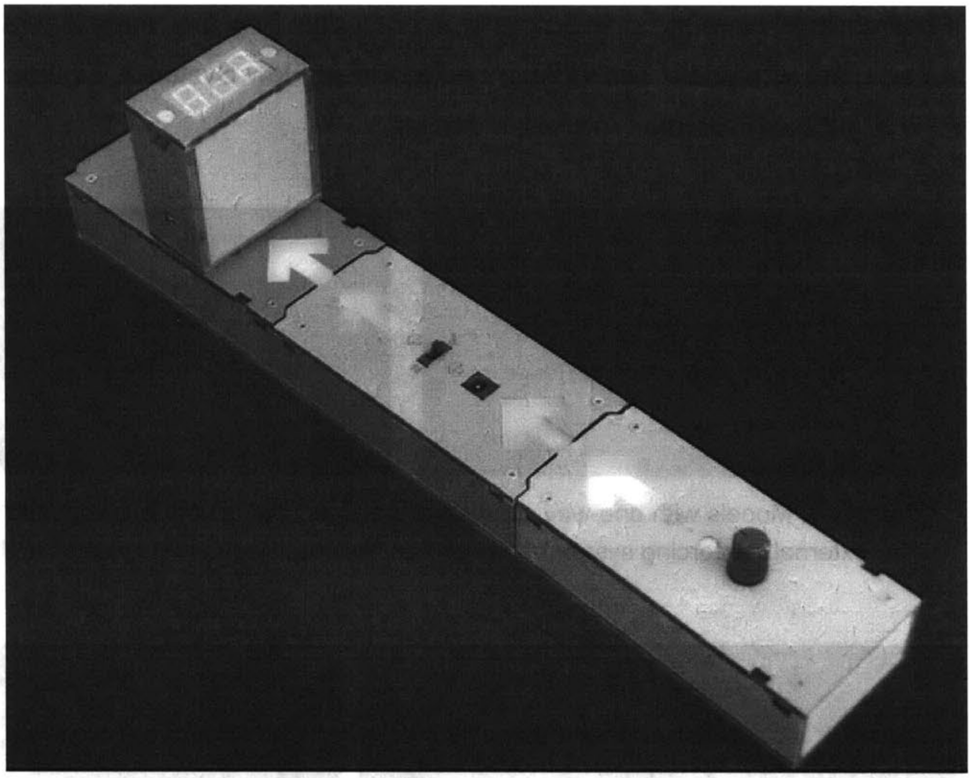


Figure 39: A FlowBlocks model of the Basic Flow System.

When children are ready for more sophisticated models, the feedback cable is introduced (the blue cable in Figure 40). Starting with the Basic Flow System and connecting the feedback cable from the Accumulator display to the Inflow dial, will form a "positive feedback loop" or a self-reinforcing system. On the other hand, connecting the feedback cable from the Accumulator display to the Outflow dial, will form a "negative feedback loop" or a self-regulating system.

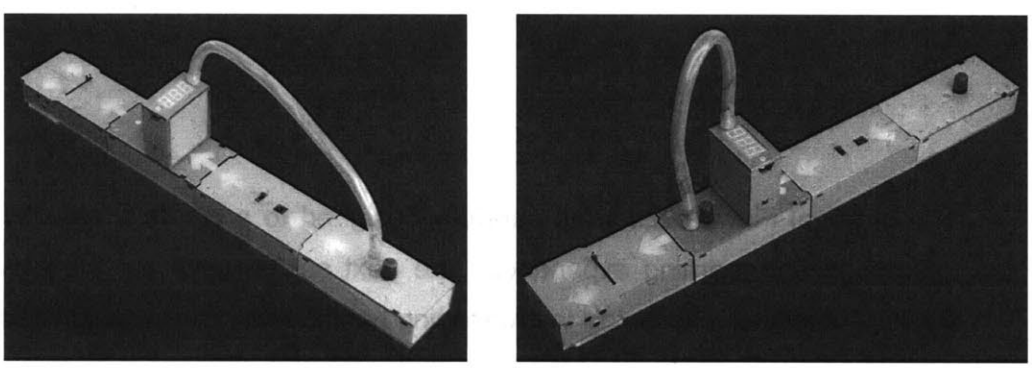


Figure 40: Using the feedback cable and the Basic Flow System to form a positive feedback loop or a self-reinforcing model (left) and a negative feedback loop or a self-regulating model (right).

When children have assimilated this type of models they are ready to move on to the next set of models: two interconnected Basic Flow Systems. Figures 41 and 42 lays out the 4 common models in that set.

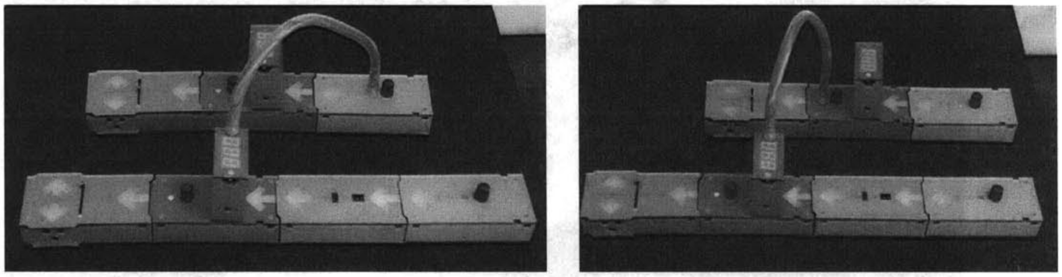


Figure 41: Models with one-way connection between two Basic Flow Systems.
An "external reinforcing system" (left) and an "external regulating system" (right).

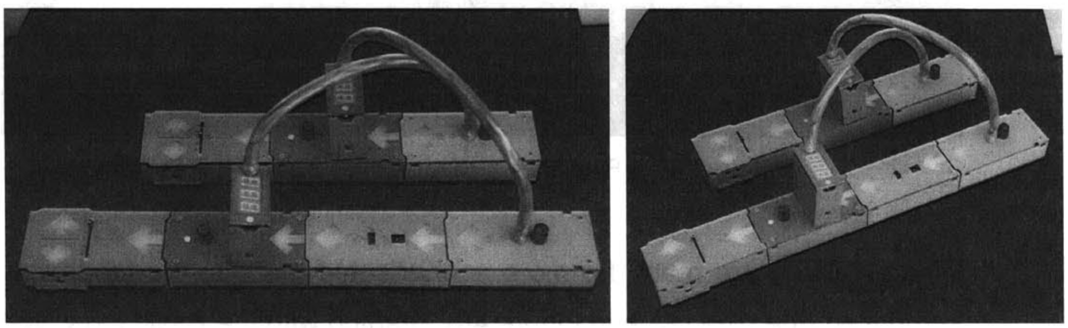


Figure 42: Models with two-way connections between two Basic Flow Systems.
A "mutual reinforcing system" (left) and an "oscillating system" (right).

The physical FlowBlocks were carefully designed to promote a specific type of interaction and learning experience. The next section lays out the FlowBlocks Design Principles, explaining the reasoning behind this careful design decisions.

FlowBlocks Design Principles

The physical FlowBlocks were designed according to the following design principles:

1. Create a ***computational construction kit***
2. Engage through ***conceptual manipulation***
3. Benefit from ***TUI advantages***
4. Encourage ***meaningful behavior-level analogies***
5. Promote ***collaboration***

Design principle 1: Create a computational construction kit

A construction kit is a set of physical building blocks that fit together in a mechanical way according to specific pre-designed rules, forming a coherent system that enables children to form many different configurations. Building blocks systems are designed in such a way that during a play process, a child can learn the rules by trial-and-error and is able to create a variety of models. With child-appropriate scaffolding, children can discover more meaningful models, and over time reach different levels of "mastery" and form more advanced models more naturally.

Examples for construction kits are LEGO bricks, Knex, Erector, Tinker Toys, Fischertechnik, Lincoln Logs, Zoob, Geomag, and many others.

In the electronics era, digital "building blocks" systems have been created. Since computation is involved, these new systems usually involve construction and representation of interactive, dynamic, or programmable behavior.

In his 1993 paper, Mitch Resnick introduced "Behavior Construction Kits": "Whereas first-generation construction kits allowed children to build structures, and second-generation kits allowed them to build mechanisms, our third-generation kits allow children to build behaviors." (Resnick 1993).

In 1998, Resnick introduced Digital Manipulatives: "These new manipulatives -- with computational power embedded inside -- are designed to expand the range of concepts that children can explore through direct manipulation, enabling children to learn concepts that were previously considered 'too advanced' for children." (Resnick 1998)

Examples for Digital Manipulatives include The Mindstorms robotics kit from LEGO; the Cricket invention kit from the Playful Invention company; Active Cubes from Osaka university (Ichida et al. 2004); Triangles (Gorbet et al. 1998), Curlybot (Frei et al. 2000), and Topobo (Raffle 2004) from Hiroshi Ishii's Tangible Media group; Block Jam (Newton-Dunn et al. 2003) from Sony design; Suzuki & Kato's AlgoBlocks programming language (Suzuki and Kato 1995); McNerney's Tangible Programming Bricks (McNerney 2004); and Wyeth's Electronic Blocks (Wyeth, 2001).

When designing FlowBlocks, I wanted to create a new type of computational construction kit, one that focuses on conceptual manipulation rather than design of visually-meaningful structures. More about that in design principle 2.

Design principle 1 as manifested in FlowBlocks:

1. The physical blocks fit together as a coherent physical "building blocks" system.
2. A "trial-and-error" exploration makes it possible to discover the rules underlying the language.
3. Over time a child can "master" the language and form more complex models more naturally.

Design principle 2: Engage through conceptual manipulation

Montessori objects engage through conceptual manipulation, not through visual analogies. The physical manipulation process is not aimed at creating models or configurations that are visually similar or structurally similar to real-world structures (such as house, castle, bridge, person), or configurations that are aesthetically interesting or appealing (such as visual patterns). Rather, the physical manipulation process is aimed at one goal: surfacing a specific abstract concept.

Montessori carefully documented how engaged children can be in a conceptual manipulation process. She called it "polarization of attention", meaning that children enter into a "zone" of deep engagement and their complete attention is directed internally, to their mind-hand interaction. In the background section of this thesis (page 21) I included a quote from Montessori's writings describing the "polarization of attention" of a young girl playing with the cylinder toy.

I was fascinated by this quote and by Montessori's design style that engage children on a conceptual level. Montessori's designs reveal several principles that support conceptual manipulation, including: discourage visual or structural analogies, represent one main abstract concept per object, and introduce constraints to guide the child towards the essence.

On the other hand, Froebel's "construction kit" designs allow children to explore many different configurations, and reach the more meaningful ones through an iterative process of trail-and-error.

My goal was to create a new type of Learning Object, a design that is both "conceptual manipulation" & "construction kit". A Montessori-inspired manipulative that engage children on a conceptual level, but at the same time a Froebel-inspired building blocks system, that enable children to explore many configurations.

To achieve this goal I designed a physical building blocks system that is "tightly coupled" with a conceptual language. "Tightly coupled" means that each physical building block is representing one concept, one building block from the conceptual language, so the mapping between the two languages (physical and conceptual) is bi-directional.

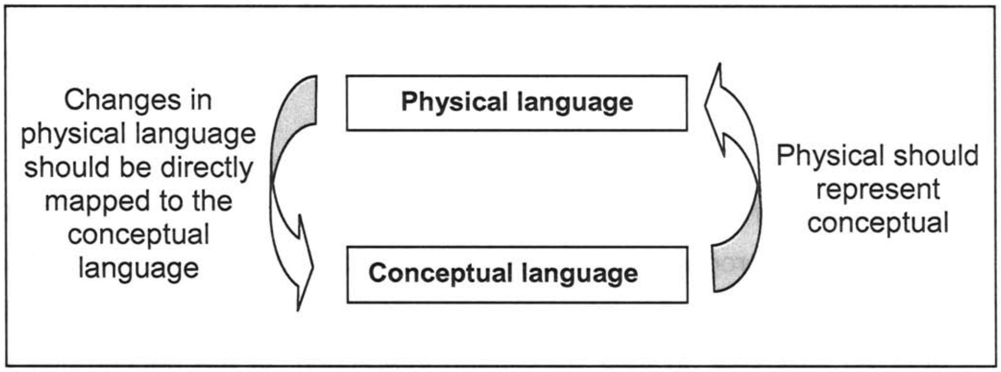


Figure 43: A "conceptual manipulation construction kit"

A Conceptual Manipulation Construction Kit is formed of two systems, a physical "building blocks" system, and a conceptual language. These two "languages" should be "tightly coupled". The physical and visual aspects of the physical system should reflect and represent the conceptual language, and any changes in the configuration of the physical system should be directly mapped to appropriate changes in the conceptual language.

Design principle 2 as manifested in FlowBlocks:

1. "Tightly coupled" conceptual manipulation construction kit: the conceptual language is mapped directly to the building blocks system. Each of the physical blocks represents an element from the Flowness modeling language; so all possible physical models are valid and can be simulated.
2. The concepts mapped to the building blocks are: Discrete and Continuous Inflow (Rate); Accumulation; Outflow (Rate); Probabilistic Distribution; More-is-more influence (Feedback); More-is-less influence (Feedback).
3. The simulated dynamic behaviors are: Linear Growth, Linear Decay, Rate-of-change, Dynamic Equilibrium, Exponential Growth, Exponential Decay, Oscillation, Conservation of Matter.

4. Discourage visual or structural analogies through carefully designed physical constraints: large building blocks; a fixed 90 degrees angle between all blocks; support of 2D structures only.
5. Focus on a main abstract concept: visualizing dynamic processes using light sequences and the illusion of continuous flow.
6. Isolation of properties: If the physical form has strong affordances for the behavior layer, there is no need to over-emphasize it. For example, The Straight, Turn, and Distribute blocks are all the same color (Blue), because the transparent arrows are already representing the behavior layer in a clear way (the direction the light will travel).

Design principle 3: Benefit from TUI advantages

Tangible User Interfaces (TUI) are physical environments that control & represent digital information. In 1997 Hiroshi Ishii published his Tangible Bits vision: "Tangible Bits allows users to 'grasp & manipulate' bits in the center of users' attention by coupling the bits with everyday physical objects and architectural surfaces…The goal of Tangible Bits is to bridge the gaps between both cyberspace and the physical environment…" (Ishii 1997).

The TUI-4D framework (Tangible User Interfaces - 4 Dimensions of coupling) focuses on the core aspects of TUI: ***Tangible Manipulation & Control***, and ***Tangible Representation*** – and the four dimensions of coupling between them. The tighter the coupling between these two aspects, the tighter is the feedback loop between the user action and the digital reaction, which results in a more natural interaction (see Figure 44).

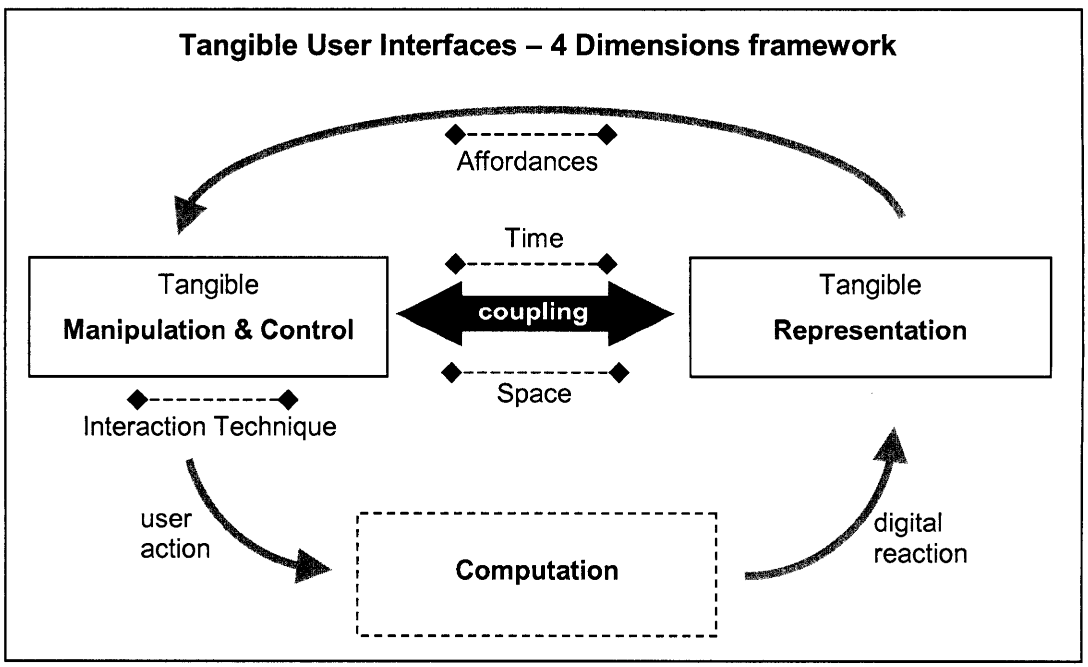


Figure 44: The TUI-4D framework for Tangible User Interfaces

There are four dimensions to the TUI-4D framework:

- ***Interaction Technique***: can the user interact with both hands simultaneously? does the interaction technique leverages humans' lifelong expertise with two-hand interaction?
- ***Coupling in Time***: how much time passes between action & reaction?
- ***Coupling in Space***: how far is the reaction location from the action location?
- ***Affordances***: how familiar are the affordances used in the design? What physical & visual aspects inform the user on the expected interaction and possible outcomes?

For clarification, here are a few examples from the toys, games & gadgets industry:

A train set or marble run has a weak coupling in time: when a child wants to changes the path of the train or the marble, she first make the change and only then runs the train or marble through the new path. In contrast, a remote-control car has a strong coupling in time: when a child wants to change the path of the car she moves one of the controls and the change happens immediately.

A PC-based video game has a weak coupling in space: the game is controlled through the keyboard or mouse, which are not physically adjacent to the screen. In contrast, a GameBoy portable game device has a relatively strong coupling in space: the user control and digital display are physically adjacent, although not yet at the exact same space. LeapFrog's LeapPad reading system has a strong coupling space: children use a stylus to touch the words they want to hear. Fisher Price's PowerTouch reading system has an even stronger coupling in space: children use their finger tips to touch the words they want to hear. Another recent example is Apple's iPhone's finger-scrolling feature.

A mouse that controls an on-screen cursor has a poor metaphor but strong affordances. It has poor metaphor because its name, shape, or visual features do not convey anything about what the mouse represents. It has strong affordances because the mouse's shape invites us to lay our hand on it and move it around.

Design principle 3 as manifested in FlowBlocks:

1. Tangible Manipulation & Control: arranging blocks in different configurations leverage humans expertise with two-hand interaction; buttons and knobs are familiar and intuitive to use; the decentralized control enables many children to interact simultaneously.
2. Tangible Representation: translucent arrows shapes on blocks represent the causal language; moving lights represent the dynamic processes.
3. Coupling in Time: tight coupling, user actions (such as generating flows through dials and buttons) has an immediate effect on the moving lights; hot-swapping of blocks is possible and changes the simulation in real-time.
4. Coupling is Space: tight coupling. User actions and digital reaction are on the same object (the dynamic processes are simulated on the blocks using the moving light).
5. Affordances & Metaphors: The blocks' connectors guide the user towards the right way of connecting blocks together (using the physical indent and the magnetic attraction); Sequences of light are a metaphor for flow.

Design principle 4: Encourage meaningful behavior-level analogies

FlowBlocks are designed to promote conceptual manipulation, and therefore create a rather abstract experience for children. Engaging and playful, yet abstract. When children play with FlowBlocks for the first time, they usually try to form visual or geometric structures that are familiar to them, such as letters, numbers, airplanes, and houses. They often start by making examples and analogies on the structure level, how things look, and miss the behavior level, how things behave. I wanted to design FlowBlocks in a way that will help children gradually shift their focus from the surface level of the geometric structures to the deeper level of the underlying behavior. In 2006 I published a study showing how FlowBlocks can be used as a conceptual bridge between understanding the structure and behavior of a complex causal system (Zuckerman, Grotzer, Leahy 2006). In the evaluation section of this thesis there are more details about that study.

When children make models with construction kits they intuitively make analogies based on the geometric, structural, and visual features of their creations. I wanted to design FlowBlocks in such a way that will naturally promote behavior-level analogies.

Design principle 4 as manifested in FlowBlocks:

1. Discourage immediate visual analogies: As described in principle 2 (conceptual manipulation), FlowBlocks' design constraints discourage children from forming structures that look like letters, numbers, houses, or towers. That helps children notice the rules underlying the moving lights and discover the behavior-level.
2. Provide a mechanism for mapping behavior-level analogies: Sets of ready-made example-cards are prepared so children can map them to the blocks, signifying what a block represents in a certain simulation. The example-cards have graphics and/or text labels. The children place the cards on or beside certain blocks, and can then use the examples on the cards to tell a story, which is the real-life analogy for the generic simulation. The cards have no

technology component, so the child does the mapping independently. A child can map the cards in a wrong order, but then the story making on top of the simulation would not make sense, and the child could realize that the mapping should be changed. In addition, the example-cards mapping activity surface the child's mental model, and allows an observer to better understand the child's thinking.

3. Provide a mechanism for child-created analogies: Sets of blank example-cards are available for the children to write/draw their own example. This allows children to make up examples that are meaningful to their own lives, and changes the whole experience to a more personalized and meaningful one. The familiar format of a paper card allows children to quickly write or draw with no learning curve, and the ephemeral nature of the cards promotes a supportive atmosphere for quick drafting of ideas.

Design Principle 5: Promote collaboration

Collaborative learning experiences provide opportunities for collaborative sense-making and expose children to multiple points of views.

Collaborative sense-making happens when a group of children tinker with a new tool or object, and each of the group members have the potential to contribute to the overall progress of the group. One child tries one configuration while another tries a different one; children look at their peers to see how they progress; children can use intuitive body movement and speech to signal when they achieves some progress; etc. This way, the whole group is progressing as one unit, when one child achieves some progress her learning is immediately distributed among the group's members.

Exposing children to multiple points of views is critical when trying to teach new ways of thinking about the world. A collaborative learning experience can promote it by providing opportunities for sharing one's point of view, by making models & simulations visible to the whole group, and by promoting individual examples.

A designer of a new learning technology can "design for collaboration", creating a digital learning environment that:

- Promotes face-to-face interaction
- Enables group observation and analysis
- Promotes multi-user control
- Provide entry points for children with different strengths and style of learning

Design principle 5 as manifested in FlowBlocks:

1. Promote face-to-face interaction: FlowBlocks are designed as a tangible User Interface and are used on regular tables, providing a natural experience that fit perfectly into a group face-to-face discussion; the blank example-cards

enable children to share their examples and stories with the group that can develop into meaningful discussions.

2. Enable group observation and analysis: The light sequences are visible to everyone that seats around the table, so observation & analysis of the unfolding simulation is natural.
3. Promote multi-user control & contribution: FlowBlocks support "multi-hand" interaction (children configuring blocks structures, turning dials).
4. Provide entry points for children with different strengths and styles of learning: The blocks provide a tactile experience for little builders; the moving lights provide a visual experience; the dynamic processes & analogies provide a cognitive as well as conceptual experience; the example-cards provide opportunities for drawing and writing and enhance discussion.
5. FlowBlocks workshop: In the FlowBlocks workshops small groups of people interact with FlowBlocks together, forming a collaborative learning experience that surface the multiple points of views children have about the world around them.

FlowBlocks Technical Implementation

FlowBlocks are made from laser-cut Basswood and Plexiglas parts, which are glued together to form a box. The Basswood blocks are painted and sanded. The hardware is a 10 MHz PIC18F252 microcontroller mounted on a dedicated printed-circuit-board that handles power distribution, local processing, A/D conversion, and 16bit serial network communication (see Figure 48). Four AAA batteries (5-6V) provide power the whole system. The batteries are mounted inside the Straight block (the green one in the photographs) and power is distributed from block to block through the magnetic connectors.

The firmware is written in Logo (Papert 1971) and runs on a Logochip PIC18F virtual machine (Silverman, Berg, Mikhak 2002).

The custom-made magnetic connectors have male (output) and female (input) parts. The male side is composed of three neodymium pressure-formed magnets. The female part is composed of 3 loosely-connected steel screws, that move towards the male magnet connectors via the neodymium magnets attraction.

5mm superbright LEDs are used throughout the system to provide the "moving lights" representation. 7-segment LED display units are used to provide the accumulator display.

The implementation of the FlowBlocks hardware (called FlowBoard) was carried out using the instrumental help of several undergraduate students from MIT's Electrical Engineering department, through MIT's Undergraduate Research Opportunity Program. The PCB went through several design iterations and size reductions, with the final version designed & implemented by Carlos Villa-Virella.

The design of the power bus introduced several challenges. When new blocks were connected to an existing chain of blocks, the system experienced an unexpected power load. In some cases, the new load created a temporary power loss for the previous block in the chain that resets the microcontrollers for a fraction of a second.

The problem was addressed by Carlos Villa-Virella in two ways:

1. Adding a capacitor on each of the PCBs (see Figure 45).
2. Designing a diode-based Peak Detector circuit (see Figure 45, 46).

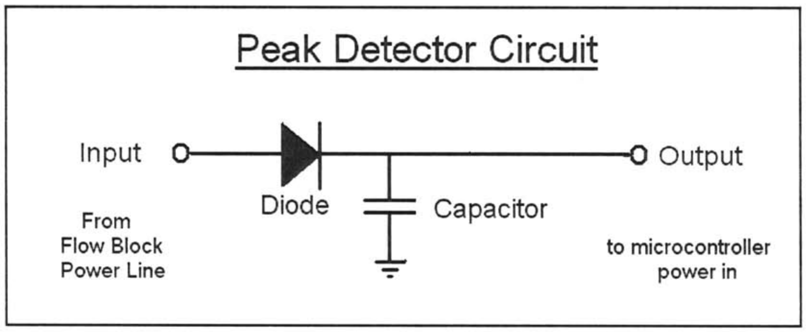


Figure 45: the diode circuit that addressed the PIC reset problem

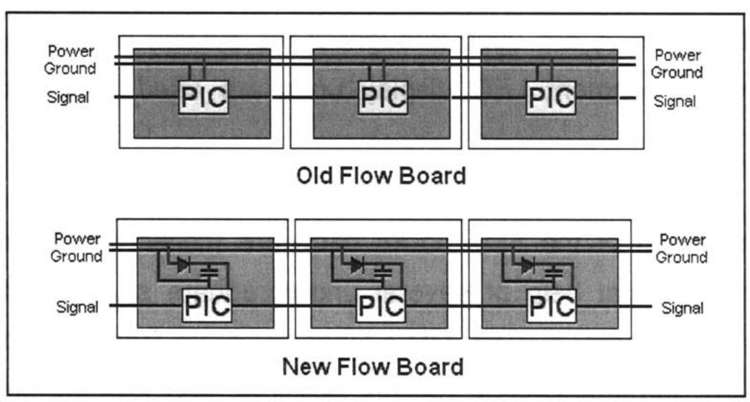


Figure 46: the new power bus design includes the diode peak detector circuit

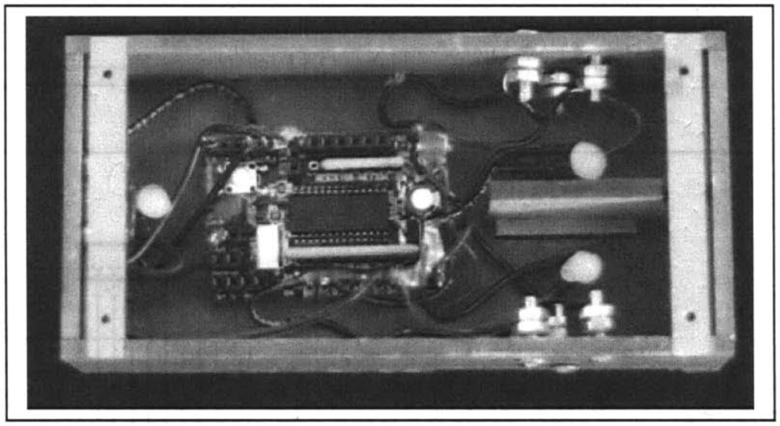


Figure 47: FlowBlock's PCB mounted in a Straight block

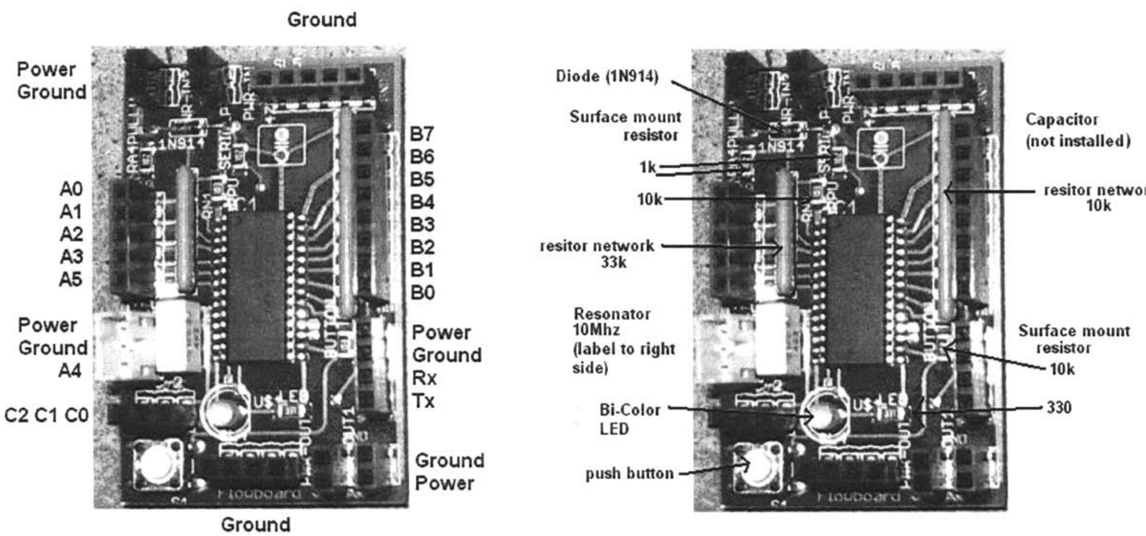


Figure 48: FlowBlock's PCB parts and ports

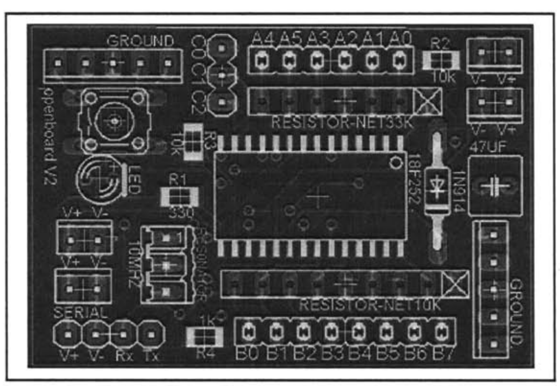


Figure 49: FlowBlock's PCB board layout (designed in Eagle by Carlos Villa-

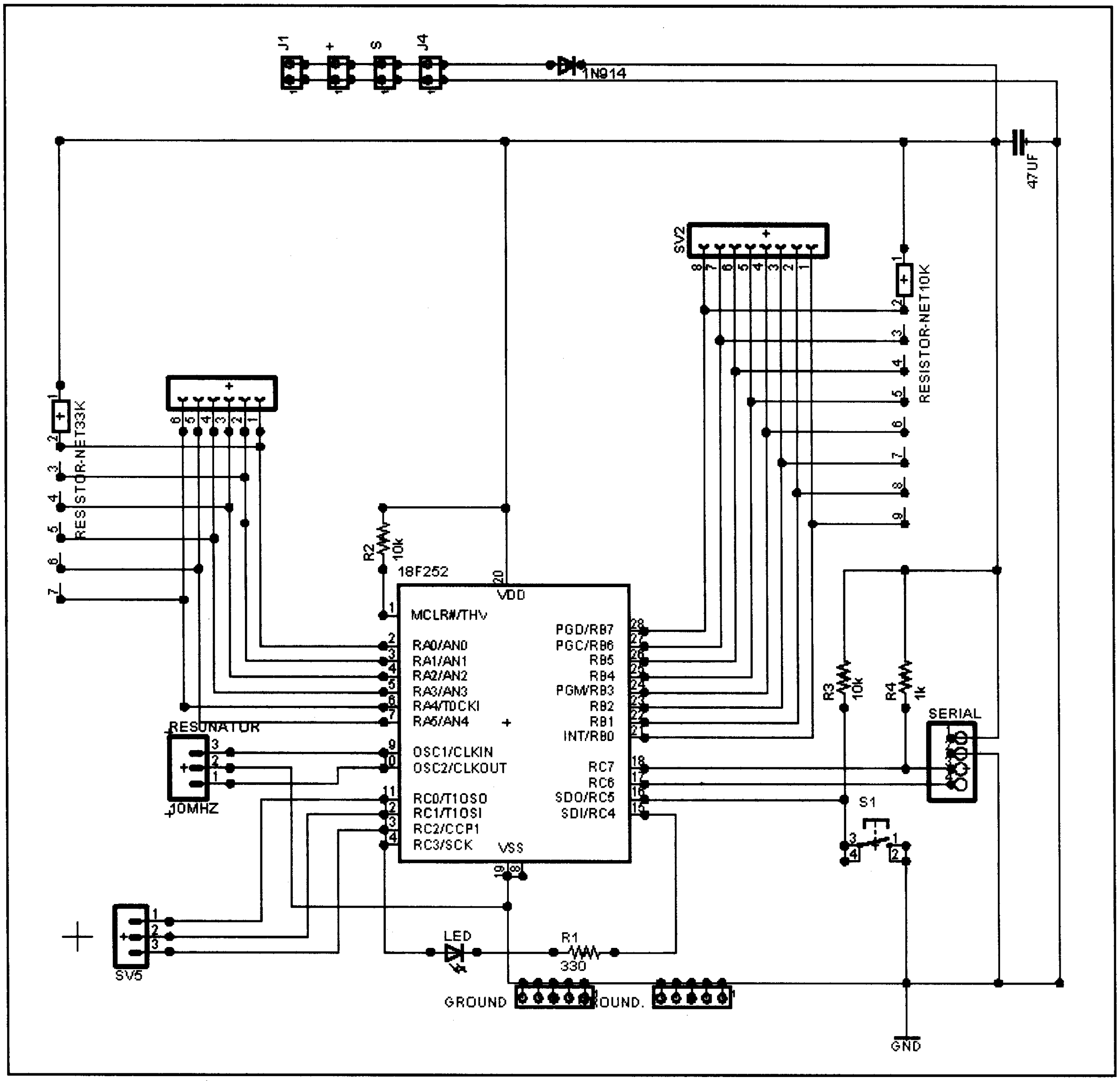


Figure 50: FlowBlock's PCB circuit design (designed in Eagle by Carlos Villa-Virella)

CHAPTER 6. EVALUATION

FlowBlocks is a rich environment for research, and can be used to facilitate a range of studies in different domains, including but not limited to: children's thinking about complex systems and complex causality; children's collaboration & interaction patterns with a tangible interface; children's range of analogy-making and the connection (or lack of) to FlowBlocks design principles; comparing free-play, guided-play and instruction-based FlowBlocks sessions and the connection (or lack of) to children's engagement and learning; and surfacing children's "mental models" or "naïve models" about the mathematics of change and dynamic processes.

For the scope of this dissertation, I focused on the domain of children's intuitive understanding of Systems concepts & their ability to connect it to causal patterns in everyday life. More specifically, I focused on the following questions:

Question 1:

> Can FlowBlocks serve as an educational scaffold for children, helping them progress from structure-level (geometrical shapes) to behavior-level (patterns of behavior) reasoning in the context of Systems Thinking?

Question 2:

> When children use FlowBlocks to explore models & simulations of dynamic systems, what are the different trajectories they move through while they transition from focusing on a simulation's surface features to focusing on the deeper underlying behavior?

Question 3:

> Can a FlowBlocks collaborative workshop help students gain a better understanding of Systems Thinking concepts, including Inflow, Accumulation, Outflow, Positive and negative Feedback?

To address these questions I have conducted the following studies:

Study 1:

The Haggerty school study, conducted together with Prof. Tina Grotzer and her student Kelly Leahy from Harvard Graduate School of Education, addressed the first question. We conducted a series of 50 minute FlowBlocks play sessions with six pairs of 4th and 5th grade students. We transcribed the sessions' video recordings, scored the children's phrases to track their progress from structure-focused terminology to behavior-focused terminology, and analyzed the results. Our findings show that with the educational scaffolding built into the blocks' design, the students were able to move beyond the structural level and focus on behavioral aspects of the causality within the system. We published our early findings in the International Conference of the Learning Sciences in June 2006

Study 2:

The Acton Discovery Museum workshop-study addressed the second and third questions. I facilitated a collaborative workshop with eleven 8th – 10th grade students who had no prior instruction in Systems concepts. The workshop had four 2-hour sessions, in which I gradually introduced Systems concepts to the workshop participants through my FlowBlocks workshop method: play & tinker; make models; map ready-made analogies; create your own daily life analogies; share your analogies with one another. I used this method in a repetitive way, gradually progressing from the most basic Systems Concepts (such as Inflow and Accumulation) to more advanced concepts (such as positive and negative feedback loops). I have conducted two evaluations with the workshop participants.

To address question 2, I asked the participants to write in their journals "what they think the blocks are about, what they are good for" at three different times during the workshop's first sessions (After 6, 30, and 100 minutes). I color-coded their answers, identifying different levels of structure-focused and behavior-focused terminology. I organized the color-coded clusters in a table to reflect the change over time, and a clear trajectory was visible. My analysis clearly shows the progress participants had throughout the first two hours of the workshop, and makes the trajectory visible, both on the individual and group level.

Study 3:

To address question 3, I documented and analyzed the Acton workshop participants' daily-life analogies in eight analogy-making activities that took place at three of the four workshop sessions. I classified the examples as correct or incorrect, and for each incorrect one I concluded which misconception is involved, based on my Masters thesis classification of children's barriers to learning Stock & Flow modeling. My analysis shows a clear improvement in the number of correct analogies for models that involve Inflow, Stock, and Outflow, as the workshop progress. In addition, my analysis shows an impressive number of correct examples for the more advanced concepts, the positive and negative feedback models, documented in the third session. One explanation is that the hands-on FlowBlocks experience the students had is both on the interaction level and conceptual level, creating the appropriate foundation for learning more advanced concepts in a relatively short time. I have not designed a formal measurement to evaluate children's understanding of these concepts, and have not conducted pre and post tests. Nevertheless, the "Acton Analogies Study" shows that children with no prior instruction in Systems Thinking can learn and develop a good intuitive understanding of Systems concepts such as Inflow, Stock, Outflow, Positive Feedback, and Negative Feedback. On a more general level, it strengthens my assumption that FlowBlocks can serve as an effective learning aid to introduce children to Systems Thinking concepts in a hands-on collaborative process of playful modeling.

Study 1: The Haggerty "Bridge" Study

The Haggerty study was conducted in 2006 in collaboration with Prof. Tina Grotzer and her graduate student Kelly Leahy from the Harvard Graduate School of Education. We have published this study at the International Conference of the Learning Sciences in June 2006. Following are selected excerpts from the introduction, methodology, and findings sections.

Research shows that very young children hold fragile developing concepts related to forms of complex causality. Hmelo, Holton, and Kolodner (2000) introduced the Structure-Behavior-Function framework (SBF) in the context of complex systems. Borrowed from systems approaches to artificial intelligence (Goel & Chandrasekran, 1989), it draws distinctions between structures, functions, and behaviors of systems and the connections between them to illuminate types of reasoning about systems. According to Hmelo and colleagues (2000), structure refers to the actual physical structures of a system, such as the lungs and alveoli, function refers to the purpose of the system or subsystem, so the transport of oxygen throughout the body, and behavior refers to the dynamic mechanisms and processes that enable the structures to carry out their function. Hmelo-Silver and colleagues (Hmelo-Silver, Pfeffer, & Malhotra, 2003) found that students were more likely to perceive the structural aspects of a system and to miss the behavioral or functional aspects. Using an aquarium as a ecosystem, they found that children and novices assumed that the role of plants in an aquarium is decorative only, that the plants are there to please the viewer--exemplifying how novices focus on the physical, visible parts of a system, or the structural level. People with greater expertise in the subject matter (such as teachers, aquarium enthusiastic, or academic experts) were able to separate between the structure and behavior levels, reasoning about the role of the plant in the aquarium and its interaction with other components.

Haggerty Study Methodology

Design: We conducted an exploratory study focused on children's ability to make the transition between physical or structural components of a system to behavioral or processes within a system.

Participants: Fourth and fifth grade students (n = 18) from the Haggerty school in Cambridge, MA with an ethnically and socio-economically diverse population participated in the study. The students received no formal exposure to systems-thinking or complex causality concepts. Eight fifth graders, with even representation from each gender, and ten fourth graders, with a higher representation of girls (eight girls and two boys) comprised the interviewees. Classroom teachers selected the students for participation. Teachers were asked to select students who were average achievers from those who had returned parental permission slips.

Procedure: Each student participated in one 50-60 minute session exploring FlowBlocks with one other student of the same age and gender, and myself as the interviewer. The students were paired with another student to encourage communication between them and offer a window into their thinking with minimal researcher probing. Each session was videotaped for later analysis.

The interview technique proceeded from little researcher support (highly open-ended) to increasingly scaffolded questioning. The interview was comprised of three sections. In the first part of the session, the students were given a basic introduction to the blocks. I told them what each block did in a technical sense and demonstrated how to connect the blocks. The students were given a limited set of blocks to start with, and new blocks were added in parallel with the students' progress. I handed the blocks to the students and said, "Let's see what you can do with the blocks." I was careful not to use terms such as "build" that would imply one type of focus (structural, for example) over others (behavioral or functional, for example). After a few minutes, I added, "Try to explore different configurations. Let me know when you are done exploring this set and ready to move on." When students said they were ready to move on, I added two more blocks. The additional blocks enabled the completion of a closed cycle.

The constraints in the blocks' design (see Design Principle 2 in the "Designing a New Learning Technology" chapter) are intended to guide the students toward cyclic structures and the investigation of the behavior of circular causality. When the students formed a closed cycle, I asked them to explain using non-leading probes such as "Can you tell me about what you are doing?" or "Can you tell me about what you made?"

In the second part of the interview, I added two more blocks, to enable the creation of a non-symmetric loop, and said to the students, "Let's see what you can do with this set of blocks." After 10 minutes, if the students had not created the non-symmetric loop, I presented a picture of one and said, "Another student made this and called it a 'circle', is this 'circle' similar or different than the previous ones you formed?" If the students only mentioned similarities, I probed for differences and vice versa.

Coding and Analysis: The videotaped sessions were transcribed, and coders worked from the transcriptions and the videotape. They were coded independently by two researchers for statements that indicated a focus on structure and on behavior of a system. The researchers coded for statements that suggested whether students were focusing on structural (geometrical shapes) or behavioral (patterns of behavior) features of the blocks.

Haggerty "Bridge" Study Findings & Discussion

Most students began by forming configurations with the blocks. Their comments suggested a clear focus on the physical, structural aspects of the blocks. In the following excerpts from the interviews transcripts, the letter 'I' represents the interviewer.

K: You could build a city.

T: Yeah. With the longest….the sens….

K: A giant road.

T: San Francis… Oh man, I can't say this.

K: What?

T: San Francisco Bridge or something.

I: San Francisco?

T: Yeah, bridge.

K: Oh, the San Francisco bridge.

I: The Golden Gate.

T: Bridge.

K: Yeah, the red one?

T: And that's the way to go.

I: What are you trying to make?

K: A square.

T: It looks kinda like a snake.

I: Like a snake?

T: A sneaky snake.

I: Ok.

T: And that's the head.

I: Ok. It looks like a snake.

T: And those are the eyes and that's the nose.

I: Ok.

T: And that's the mark on it.

As the students gained more 'play time' with the FlowBlocks, they started to differentiate between the physical configuration and the behavior of the blocks. A few students did begin with a behavioral focus and attended immediately to the pattern of the lights. There was clear evidence that the students distinguished between the physical structure of the blocks and the patterns of the light. They were quite articulate about the difference between geometrical shapes and patterns of behavior. Some of the students also showed a clear focus on the relationship between pattern and behavior. They revealed terminology for distinguishing pattern from physical structure ("repeatedly", "circulating" "self-contained").

I: Ok. And what do you think about this shape? What would you call this one?

C: Um, a square.

I: A square?

A: A circle.

I: Circle?

C: Square or circle.

A: Well, for this it would be like a circle because…

C: Yeah, um, geometrically it's like a square.

A: A square.

C: But if, like, we're using circuits and stuff you would refer to it as a circle.

A: It depends on what kind of shape, because this is, like, a rectangle, and you couldn't make a circle out of it, so it would be a circle sort of.

I: So what's circle about it? Is it like, geometrically it's a square, right?

C: Yeah.

I: So, but circle is still a good name for it?

C: Yeah, well if you're only, if you're able to talk about, like, um, how you, I don't know how to explain it exactly. Say you wanna talk about how you're using, um, like, circuits and batteries, you would, um….I, like… Ok, so this would be, you would say it's a circle if you're only talking about using a circuit or a battery or something, but… if you're, like, if you want, if you wanna talk about, like, geometrically what shape it is you would say it was a square.

I: Ok. So if you talk about the circuit it's a circle and if you talk about the geometrical shape it's a square?

C: Yeah.

I: What do you think A?

A: I think it would be a circle, sort of, because you can't really make a circle out of this shape. Geometry, like… it would be considered a square.

I: Um hmm.

A: But it's really it would be sorta like a circle, for this matter.

I: For this matter it's a circle?

A: Yeah.

I: Why?

A: Because it travels like that. And so, like, a circle kind of pattern.

I: Pattern? What do you mean when you say pattern?

A: Well, I mean, like, if you draw a circle it would sorta seem like you were drawing this.

K: I'm trying to make it go, make it so it can go around in a circle either way, but I could just change this completely.

S: [...inaudible...]

I: Go around in a circle, you said?

K: Yeah.

S: Yeah, go around in a circle either way.

I: What do you mean, circle?

S: Well, a square actually, I think.

K: Yeah. Well, like, so it keeps going on and on and on.

S: Like we had before, but she wants it to go on so if it's...so if it goes this way it'll go around. It won't go around okay?

K: Yeah.

S: But if it goes this way it'll go around.

I: You know that when I play with people with this, some kids say circle and some kids say square. What do you think it is?

K: Well, the shape is a square or a rectangle.

S: Yeah but technically it's going around in a circle.

K: But like, a circle you think it, like, keeps going around and around forever.

S: Yeah, so...

I: So what word do you think is better to use, or what is the difference between using them?

S: Well, a square has corners and is actually going around

K: The actual shape is this.

I: Um hmm.

K: Is a square, but, um, the concept of what you wanna do is different.

S: Than what it actually is.

I: So the circle is more of the concept?

K: Yeah.

I: Like if the rectangle is a shape, so what is a circle?

S: A circle is a shape, but it's going around in a pattern that much like a circle.

Once students began to focus on the behavior of the lights, they seldom reverted back to discussing physical structure except in contrast with behavior or in discussing the mechanics of sticking the blocks together. The point of transition for most students was the point at which they constructed a loop and the pattern in the blocks departed from a "domino causality" to a "cyclic sequential pattern".

It took students a varying amount of time to get to this point, with some of the teams making a number of configurations (all flat on the table) as with building blocks before switching to a focus on the behavioral aspects of the blocks. But once students made this switch, they pretty quickly started to explore various possibilities for creating loops.

With the educational scaffolding built into the blocks' design, the students were able to move beyond the structural level and focus on behavioral aspects of the causality within the system. This is promising given earlier research that suggests that students have difficulty moving beyond the structural features of a system (Hmelo-Silver et al., 2003).

Study 2: The Acton "Trajectory" Study

The Acton study was conducted in 2006-2007 at the Acton Discovery Museum in Acton, MA.

Acton Study Methodology

Design: I conducted a FlowBlocks workshop in an effort to introduce Systems Thinking concepts to middle school students through hands-on exploration rather than instruction. I wanted to explore the trajectory question: *When children use FlowBlocks to explore models & simulations of dynamic systems, what are the different trajectories they move through while they transition from focusing on a simulation's surface features to focusing on the deeper underlying behavior?*

Participants: 11 students (13-15 years-old) from the Acton area came to the Acton discovery museum to participate in the FlowBlocks workshop. The Acton Discovery Museum Education Director selected the workshop participants from a pool of middle-school students that volunteer at the museum.

Procedure: The students participated in 4 sessions, each session 2 hours. The "Trajectory Study" was conducted in the first session. I was the workshop facilitator.

The protocol of the first session (WF is Workshop Facilitator):

Minutes	Activity Title	Activity Description
0-2	Introduction	WF introduces about playful learning, kindergarten manipulatives, then introduces blocks and shows how to put the blocks together
2-6	Free play session	Students explore the blocks and their functionality in an open-ended way (total 4 minutes play time)
6-8	**First journal writing**	Students write in their journal their answer to the WF's question: "what do you think this is about, what do you think its good for, very quick, whatever you think about, just one line is good enough"
8-10	Presenting answers and discussion	Students present their answers to the group, with some discussion here and there

10-20	Free play continue with more blocks	WF adds the orange blocks, students continue free play session, writing in their journal about the orange block, group discussion on the orange block's role
20-22	**First cards activity: mapping ready-made examples**	WF hands over ready-made example cards for the students to map. WF instructions: "and now I'm going to give you cards, and I want you to map the cards. So the way to map the cards is to put one card on the light blue one, and one card on the orange one, and you need to choose which one is where."
23-27	Presenting examples	Students present to the group their mapping of the ready-made examples. WF instructions: "can you show us a story with this example? Take the cards off and simulate the story"
27-30	**Second journal writing**	Students write in their journal their answer to the WF's question: "what the blocks are good for, same question as before"
30-33	Presenting answers and discussion	Students present their answers to the group, with some discussion here and there
33-35	WF presents Archetype concept	WF shows a picture of a model and presents the Archetype concept: "its like a template for example, or a pattern, a specific pattern or a model, a model that we think that happens many many time, again and again…" "we did one pattern, and the pattern was: an action and something accumulates" "its like a cause and effect", "an action happens, and the effect accumulates"
35-45	**Second cards activity: mapping ready-made examples**	WF hands over another set of ready-made example cards for the students to map. This time the cards focus on examples with a long-term effect rather than an immediate effect. The FlowBlocks model used for the mapping is the cause-delays-effect model.
45-58	**Third cards activity: student invent their own examples**	WF hands over blank cards, and students write down their own original examples and map them onto the FlowBlocks model. Then students present their example to the group, with discussion here and there.
58-62	New block introduced. Free play session.	WF introduces the continuous Inflow block (instead of the discrete Inflow block), and students explore the new block in a few minutes of free-play session.
62-66	Rate-of-change exercises	WF directs the play session through a series of probe questions, such as: "can you

		decrease the accumulation?"; "can you decrease it in another way?"; "can you make the accumulation stay the same?"
66-84	**Forth cards activity: student invent their own examples**	WF hands over blank cards, and students write down their own original example for the continuous flow model, and map them onto the FlowBlocks model. Then students present their example to the group, with discussion here and there.
84-88	New concept introduced: Outflow	WF present the Outflow dial, followed by a short free play session.
88-101	**Fifth cards activity: mapping ready-made examples**	WF hands over another set of ready-made example cards for the students to map. This time the cards focus on examples that match the FlowBlocks model of Inflow-Dynamic Accumulation-Outflow. Then students present their example to the group, with discussion here and there.
101-110	**Third journal writing**	Students write in their journal their answer to the WF's question: "what do you think the blocks are good for?"
110-120	Discussion	Students give their input on the blocks as a learning environment and about specific design features.

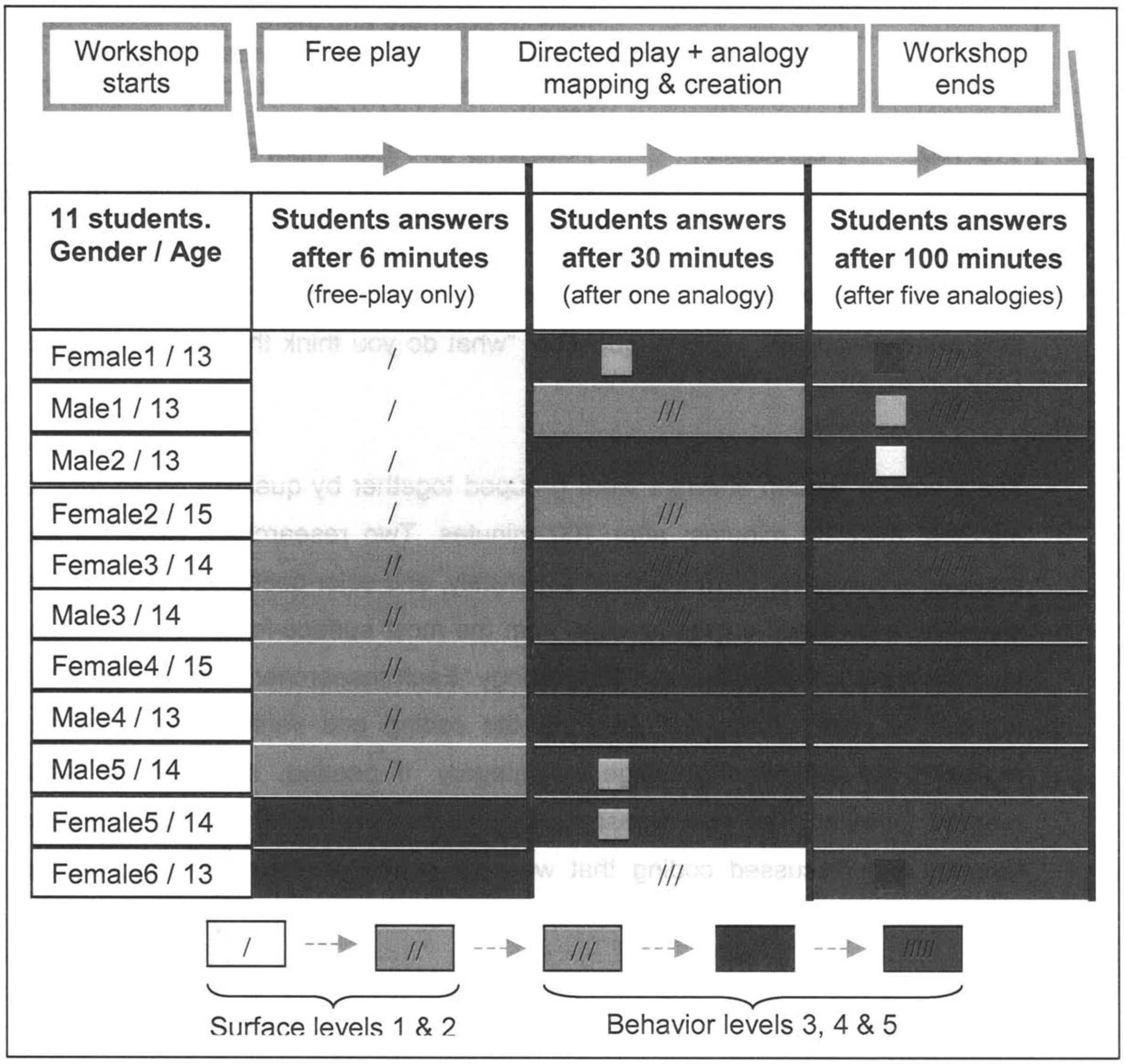
Coding and Analysis: The Students wrote in their journals three times, each time answering to them same question: "what do you think the blocks are good for?"

The students' written answers were grouped together by question order: after 6 minutes; after 30 minutes; after 100 minutes. Two researchers reviewed the grouped answers for each question separately, and color-coded key terms in the students' answers in a gradual way, from the most surface-focused terminology towards more behavior-focused terminology. Each researcher than reviewed the number of color groups formed from the coding and verified each of them represent an independent stage or category. If needed, color groups were merged together. The two researchers compared the number of color groups formed, and discussed coding that was not similar in their analysis until an agreement was reached.

Acton "Trajectory" study Findings and Discussion

The color-coding process yielded interesting results. The keywords in each category are taken from the students' writings. Aggregating the color-coded groups into a table reveals the trajectory of students' understanding.

Surface level 1 – Electricity; Circuits; Flow of Energy; Magnetic force
Surface level 2 – Movement of light; Pathway; Flow, Exploring configurations & combinations
Behavior level 3 – Model specific math problem (Counting something, adding things, calculating total) or a specific example (Bank, Garbage accumulation)
Behavior level 4 – Model & simulate general problems; Learn about concepts & patterns; cause & effect, actions, input and output, processes
Behavior level 5 – Evaluate situations; Simulate real-life experiences; Make predictions; Experiment and apply to instances in life



The color-coding categories were generated from the students written answers to the "What do you think the blocks are good for?" questions at three separate times during the workshop's first session.

1. After 6 minutes of free play activities with FlowBlocks.
2. After 30 minutes, including more directed play and analogy mapping exercise with one ready-made example.
3. After 100 minutes, including more directed play and a total of five analogy mapping exercises, three ready-made and two original examples generated by students.

Here are the students' answers with the color coding. The first group of answers are sorted in a gradual order from most surface-level to more behavior-level. The next two groups of answers are at the same order as the first one, to enable comparison. The language used is the students' exact words.

Students written answers after 6 minutes:

- **Female1 (13):** Maybe it shows electricity connections. The flow of energy? Magnets – which attracts?
- **Male1 (13):** I think there is a magnetic kind of force in the blocks so when each of them connects they send a kind of signal to each other making the circuit complete.
- **Male2 (13):** It would probably be for ***stimulating the creativity in a person's mind***. And showing how electricity moves.
- **Female2 (15):** I think these blocks show the circuit of energy flowing from the switch forward and until the last arrow.
- **Female3 (14):** understand flow, a little electrical engineering skills. Interesting to see # of combinations possible.
- **Male3 (14):** I think Flowblocks could be used on walk in the subway or airplane. Like an emergency power source, when the electricity goes out. You could change their power source to a battery. They would point to an exit.
- **Female4 (15):** The arrows have to line up head to tail – shows movement and change in direction.
- **Male4 (13):** I think this is about response to light
- **Male5 (14):** I think it shows the different path ways things can take and it shows the many twists and turns the path can take.

- **Female5 (14):** I think this is good for learning orders and [redacted]. Also it could help you through [redacted].
- **Female6 (13):** I think this is about [redacted]. Or [redacted].

Students written answers after 30 minutes:

- **Female1 (13):** maybe the blocks are good for a bank...a collection of money (account) they basically [redacted].
- **Male1 (13):** I think the blocks would be useful in counting or getting a total of something. Comparing it to walking and the distance walked its like taking a step and each time to go forward taking a step it counts up on the orange block. The orange tells you a total amount.
- **Male2 (13):** I believe the blocks are for showing [redacted], like when you press the button on the light blue block, and seeing the counter rise on the orange block.
- **Female2 (15):** Adding blocks adds length to the current. Pressing the button was like throwing the garbage in the garbage can, the trip the garbage truck took was the blocks in between and the orange counter was the garbage going in to the landfill.
- **Female3 (14):** the blocks are good for [redacted]. They show both [redacted]. Real –life experiences with multiple
- **Male3 (14):** cards show how this [redacted] like sending an email.
- **Female4 (15):** the blocks are good for showing [redacted]. Clicking the button shows how movement, and the orange block shows the total number of clicks.
- **Male4 (13):** I think this can be used as [redacted]
- **Male5 (14):** I think the blocks are good for counting things and [redacted], or accumulation or to small events.
- **Female5 (14):** I think the blocks are good for learning [redacted] and also I think they are good for calculating amounts of a certain thing, like a calculator.
- **Female6 (13):** the blocks are good for helping people count many things. Almost like a calculator. Like the equation 1+1+1+1...=total. It could help add things basically.

Students written answers after 100 minutes:

- **Female1 (13):** I think that the blocks are here to [redacted]...so we can [redacted]. [redacted].
- **Male1 (13):** the blocks [redacted]. Most people look at the cause but not at the effect that there is. For one of them the more garbage people produce the higher the pollution level rises. But if people started to recycle things slowly the trash level would decrease. [redacted].
- **Male2 (13):** After 2 hours of using them, I believe the blocks are good for teaching people about the flow of electricity, and [redacted]
- **Female2 (15):** you can also [redacted] “entering” and increasing the number on the counter as well as things “leaving” and decreasing the counter.
- **Female3 (14):** [redacted], [redacted]. [redacted].
- **Male3 (14):** Blocks can be used to [redacted] and the total accumulation constant/decrease/ or [redacted].
- **Female4 (15):** The blocks show how there can be two directions of movement that affect the result – [redacted]. Shows vectors but not by reading about them – show vectors by using them. These blocks could be really useful in a physics class because they would [redacted]. *(net increase diagram, net decrease diagram, balanced diagram).* [redacted] and how they theoretically could be solved – [redacted] – can see it more.
- **Male4 (13):** I think this could be used [redacted]
- **Male5 (14):** I think that this blocks are good for [redacted], like instead of looking at the input, we can look at the output to solve the problems. Also they teach [redacted].
- **Female5 (14):** Using the Flowblocks you can see that problems can be easily broken down into simple flow charts. This [redacted]

[redacted]. [redacted]

- **Female6 (13):** the blocks are [redacted] *(was added later?)* [redacted] Example: figuring out money + debt problems. Good for training teens with their money.

The study's findings clearly show that workshop participants do go through a transition from focusing on a simulation's surface features (in the first answers) to focusing on the deeper underlying behavior (in the second and third answers). The main activities during the session were hands-on play and simulation using FlowBlocks, and analogy-mapping activity with ready-made examples as well as original examples generated by the students. It would be interesting to conduct additional studies to better understand what type of scaffold triggers the progress in understanding: is it the ready-made example mapping, the original-examples creation, or just the play time with the blocks? In this study it was a mix of all of them.

A major factor that could influence the students' progress through the trajectory is the facilitator behavior, reinforcement, and terminology used. In this study I was the facilitator, and did not disclose the blocks purpose throughout the session. I tried to make sure I only uses terms brought up by the students, and made an effort to praise all students equally, independently from their comments or generated example. Nevertheless, it would be naïve to assume I had no influence on the students. Clearly, my choice of words, body language, and natural interaction with the group have influenced their thinking and contributed to their progress through the trajectory.

In the Procedure section above I mapped the sentences I used when I gave instructions to the students. Here is a selection from those sentences, to get an idea for the type of language I used:

Minute 20: "and now I'm going to give you cards, and I want you to map the cards. So the way to map the cards is to put one card on the light blue one, and one card on the orange one, and you need to choose which one is where."

Minute 23: “can you show us a story with this example? Take the cards off and simulate the story”

Minute 33: “An Archetype is like a template for example, or a pattern, a specific pattern or a model, a model that we think that happens many many time, again and again…”
“we did one pattern, and the pattern was: an action and something accumulates…its like a cause and effect…an action happens, and the effect accumulates”.

There is an interesting difference between the “dark-blue” and “red” color-coded categories, which represent behavior-level 4 and 5 respectively. From an understanding point of view, both categories show high level of understanding and focus on deeper behavior-level features rather than surface–level features. The “dark-blue” category represents focus on the underlying causal mechanism, the generic behavior represented in the simulation. The “red” category represents a more personally-meaningful angle, when a student connects the causal mechanism with real-life, personally-meaningful examples. A student in the “red” category does not understand more than students in the “dark-blue” category, but is appropriating the simulation in a different way.

In the second session, a week after the first one, I asked the students to write in their journals again, answering the same question: “What do you think the blocks are good for?” This time was very different than the first session, because it was immediately after I introduced the Systems Thinking language and the “Stocks and Flows” diagramming language. I also explained about my personal motivation in the project, how I wanted to cerate a learning technology that will help people “see systems” in their personal lives.

It is interesting to compare the students’ writing from that second session with the trajectory from the first session. One would expect to see more “red” categories, since I had just finished explaining to the students how Systems Thinking is about understanding the underlying patterns of situations in every-day life, and how my personal motivation in this project was to help children see the systems in their everyday lives. Surprisingly, there is almost the same amount of “red” and “dark-blue” as before.

11 students. Gender / Age	**Students answers - end of first session,** after FlowBlocks play and analogy-making	**Students answers – second session,** after Systems Thinking instruction
Female1 / 13		
Male1 / 13		
Male2 / 13		
Female2 / 15		
Female3 / 14		
Male3 / 14		
Female4 / 15		
Male4 / 13		
Male5 / 14		
Female5 / 14		
Female6 / 13		

Three students shifted from "dark-blue" to "red", but two also shifted the other way. In aggregate, there is almost no difference. This is interesting, because it might inform us that people's tendency to appropriate a concept towards real-life experiences is not influenced by direct instruction, but is rather a personal tendency. It would be interesting to further research this area. Below are the students' actual texts from the second session, with the color-coding technique. Some of the choice of words and terminology used is very well phrased and accurate.

Students written answers during the second session – the previous answers from eth children's journals were collected during the first sessions (after 6, 30, and 100 minutes into the session). This time, the answers were collected during the second session, after a "lecture-style" introduction to Systems Thinking. Students wrote in their journals, and answered the same question as the one in the first session: What do you think the blocks are good for?

- **Female1 (13)** - [redacted].

- **Male1 (13)** - the blocks show how a certain item can be used over and over again. Its like the life cycle of a person or a plastic bottle. [redacted].
- **Male2 (13)** - these blocks can be used for [redacted] and [redacted] and teaching the kids what needs to happen to [redacted].
- **Female2 (15)** - these blocks can be used to [redacted]. It's [redacted] that mostly we wouldn't think of as being a problem. [redacted].
- **Female3 (14)** - blocks can be used to help [redacted], either immediately or in a given amount of time[redacted]. Also, the blocks can help [redacted]. Finally, the blocks can [redacted]. Using these blocks, [redacted].
- **Male3 (14)** - I think they can be used to show [redacted].
- **Female4 (15)** - the blocks help explain the connection between different actions and the different steps or variables that take place in between actions. The blocks [redacted]. It shows [redacted]. It is a model of problems that you can touch and move and manipulate.
- **Male4 (13)** - no comment
- **Male5 (14)** - These are used for [redacted], and [redacted].
- **Female5 (14)** - I think the blocks can be used for [redacted]. So that we don't use all of our renewable /un-renewable resources and we are able to save them for very important needs. This will allow us to educate future generations about saving energy sources. [redacted].
- **Female6 (13)** - this block system is [redacted]. Also about learning the [redacted].

Study 3: Acton "Analogies" Study: Do They Understand the Concepts?

Understanding Dynamic Systems and Systems Thinking involves learning many new concepts. As I have discussed earlier (page 39), I have decided to focus on a specific set of Systems concepts: Stock, Flow, Positive Feedback Influence, and Negative Feedback Influence.

Research has shown that systems concepts are not well understood by novices (Dorner, 1989; Resnick, 1994; Sterman, 1994; Booth-Sweeney, 2000). Systems Thinking concepts are not easy to learn, and teaching these concepts is not easy without a simulation tool. I designed FlowBlocks as a learning aid, to help children and novices gain a better understanding of systems concepts through a hands-on collaborative process of modeling, simulation, making analogies, and discussing the analogies as a group.

> **Design:** *During the Acton workshop (described in the previous section) I conducted two sets of modeling-related activities:*
>
> - Students mapping ready-made examples onto the FlowBlocks models
> - Students creating their own examples and then mapping them onto the FlowBlocks models.
>
> I argue that students' performance on these activities is relevant to their level of understanding of systems concepts. I have not designed a formal measurement to evaluate children's understanding of these concepts, and have not conducted pre and post tests. Nevertheless, I will clearly show an improvement in the students' ability to map real-life examples onto a FlowBlocks model, and to generate their own correct examples (the participating students had no systems-related instruction prior to the workshop). I can not claim which of the workshop components increased the students' understanding: the FlowBlocks modeling & simulation activity, the analogy-making activity, or my facilitation.
>
> **Participants:** 11 students (13-15 years-old) from the Acton area that came to the Acton discovery museum to participate in the FlowBlocks workshop.

Procedure: I documented students' performance in eight analogy-making activities that took place at three of the four workshop sessions (each session was two hours long):

1. 1st session, ready-made examples: Discrete Action leads to Accumulation
2. 1st session, student-made examples: Discrete Action + delay leads to Accumulation
3. 1st session, student-made examples: Continuous Action leads to Accumulation
4. 1st session, ready-made examples: Inflow; Accumulation; Outflow (all Continuous)
5. 2nd session, student-made examples: Inflow; Accumulation; Outflow
6. 3rd session, student-made examples: again Inflow; Accumulation; Outflow
7. 3rd session, student-made examples: positive feedback (self reinforcing systems)
8. 3rd session, student-made examples: negative feedback (self regulating systems)

In each activity I handed-out different example cards. In activities involving a "ready-made examples", the cards have pre-made examples written on them; and the students' goal is to map the cards onto the FlowBlocks model in the way that makes sense to them. They map simply by placing a card on or near the block that best represents the situation written on the card. In activities involving a "student-made examples", the cards are blank; and the students' task is to invent an example that is appropriate for that specific model, write it down on the cards, and map the cards onto the FlowBlocks model.

At the end of each of the modeling activities I asked the students to present their example to the group by "simulating a story" using their example and a FlowBlocks simulation. This "peer learning" activity seems to me as crucial to the learning process, since all students are exposed to all examples, getting a chance to be inspired or influenced by their peers' examples.

Coding and Analysis:

For the ready-made examples mapping activities, I watched the workshop video recordings and classified the student's mappings as correct or incorrect. In a case of an incorrect example, I tried to further classify the type of error made by the student. For that purpose, I used the "common tendencies and misconceptions" documented in my Masters thesis:

- Narrative Causality: tendency to create sequential examples in which a cause leads to an effect which in turn leads to another effect (as a story with a beginning, middle, and end) rather than examples with simultaneous processes that are both causes or actions that influence the same effect or outcome.
- Inflow over Outflow: tendency to define the outflow as a decrease in the inflow, rather than a separate action that decreases the accumulation.
- Quantity over Process: tendency to overemphasize the stock or accumulation when mapping an example, usually by placing the Stock's card on the Inflow block, as the "beginning" of the simulated story.

For the student-made examples mapping activities, I gathered and documented all of the students' example cards. I classified the examples as correct or incorrect, again tried to further classify the incorrect ones based on my Masters thesis "misconceptions & tendencies" list, and defined each example as "Original" or "Used". A "Used" example is one that was mentioned before, either in my ready-made examples, or by one of the other students in the workshop.

Acton "Analogies" Study – Findings and Discussion

In this section I present the data and examples-classification from the eight mapping activities. The analysis of the students' mapping in those activities shows they understand the concepts of Inflow, Stock (Accumulation), Outflow, Positive Feedback, and Negative Feedback.

In the Inflow-Stock-Outflow models there is a clear improvement through the first few modeling activities (in the 1st session), and by the 2nd session there is a clear improvement in the number of correct mappings for student-generated examples. I also learned that student with a strong tendency towards narrative causality or preference of Inflow over Outflow (see the coding and analysis section above), that persists over a few activities, do not shake those tendencies during the workshop sessions, and probably need more individual attention to help them progress.

In the Positive and Negative Feedback activities there was a very impressive number of correct mapping and original, interesting examples (see activities 7 & 8). In addition, these concepts were introduced in a relatively short period of time (20-30 minutes each). There were fewer students in those activities (six out of the original eleven, due to an unexpected delay in sessions 3 and 4 of the workshop). One explanation for the high success rate can be that the students that made the extra effort to come even after the date change were more motivated and interested in this type of concepts. Nevertheless, the relative complexity of these concepts and the level of examples generated by the students support my hypothesis: that FlowBlocks can serve as an effective learning aid to introduce children to Systems Thinking concepts in a hands-on collaborative process of play & tinker; make models; map ready-made analogies; create daily life analogies; and share your analogies with the group.

The following are the detailed findings from each of the activities, including the specific examples mapped or generated by the students and my analysis & classification of the example's mapping.

1. **Ready-made examples: Discrete Action leads to Accumulation**
   Time occurred: Minute 20-22 in the first session

   In this activity I handed out ready-made example cards and asked the children to map them onto the FlowBlocks model they had formed before: Discrete Inflow (the button block) connects to an Accumulator. Each student received a different set of cards to map. Each example had two cards: one represents an action and one represent an accumulation. The students have to figure out on their own which one should be first (the action) and which one should follow (the accumulation). The goal of this activity is to verify the students understand the difference between a cause and effect, to practice the method of making analogies using the blocks as a model &

simulation, and to give the students some correct examples as a base for the examples they will invent later on.

My Example Cards	Mapping Analysis	More details
Inflow: Deposit $1 into my bank account **Stock**: My balance	Correct mapping	Mapping was easy and intuitive for all students
Inflow: I exercise/workout for 15 minutes **Stock**: Calories I burned	Correct mapping	
Inflow: Someone buys an iPod **Stock**: Apple's revenues	Correct mapping	
Inflow: Talking for 1 minutes on my cell phone **Stock**: Number of minutes I talked	Correct mapping	
Inflow: I download an MP3 file **Stock**: Number of songs in my music collection	Correct mapping	
Inflow: Reading an article online **Stock**: Gaining knowledge	Correct mapping	
Inflow: Taking a step **Stock**: Distance I walked	Correct mapping	
Inflow: Digging in the sand **Stock**: Size of hole	Correct mapping	
Summary: 20 minutes after they were introduced to FlowBlocks, students had no problem mapping the Action and Accumulation as cause and effect respectively.		

2. **Student-made examples: Discrete Action + delay leads to Accumulation** Time occurred: Minute 45-58 in the first session

In this activity I handed out blank cards and instructed the students to invent their own examples, map their examples onto the FlowBlocks model, and present their examples to the group. The FlowBlocks model was: Discrete Inflow (the button block) leads to several Straight Blocks and then lead into the Accumulator block.

The students had to figure out on their own how many cards to create and how to map the different cards onto the FlowBlocks model.

The goal of this activity was to evaluate if the students create a set of an action-accumulations cards, where the Accumulation is directly affected by the Action. The in-between cards that represent the time delay are not critical, so it does not matter for this activity if they included it or not.

Students' Example Cards	Mapping Analysis	More details
Inflow + delay: Buy cell phone; Talk on it. **Stock**: Get bill on how many minutes spent	Incorrect mapping: no repetitive action, no clear accumulation.	Not an original example (was mentioned before). Buying a cell phone is not a repetitive action, talking on it is. Getting a bill is not an accumulation, the bill itself is. Correct mapping would be: talking; number of minutes in bill
Inflow: Playing a note of a song **Stock**: How much of the song you played	Correct mapping.	An original example. Playing a note is a repetitive action. How much is played is the accumulation of that action.
Inflow + delay: Snowboarder start at top of hill; Come down mountain; **Stock**: Bottom of mountain - time took you	Incorrect mapping: no repetitive action.	An original example. Starting at the top is not a repetitive action, going down the mountain is. Correct mapping would be: sliding one more foot down the mountain; time it took.
Inflow + Delay: You pass in an essay; Your teacher grades the essay **Stock**: You get your grade on the essay	Incorrect mapping: no accumulation.	An original example. Action is ok, but there is no accumulation.
Inflow + Delay: Terrorist plan 9/11; Terrorists execute 9/11; People afraid & upset; Start a war to stop terrorists;	Incorrect mapping: no repetitive action. Good accumulation.	An original example. A great topic with an action and long-term implications, but – the action is not repetitive.

Stock: Number of people dead		
Inflow + Delay: Find book in library; Read book **Stock**: Finish book	Incorrect mapping: no repetitive action, no accumulation.	An original example. Finding a book is not a repetitive action. Reading the book is. Correct mapping would be: reading a page in a library book; how many pages I read so far.
Inflow + Delay: Getting a job; Working; **Stock**: Getting paid	Incorrect mapping: no repetitive action, no accumulation.	An original example. Getting a job is not a repetitive action, working is. Getting paid is not an accumulation but an action. Correct mapping would be: working for one hour or day; Amount of money earned
Inflow + Delay: Pay attention in class; Understand concepts; Study hard for test; Take test carefully **Stock**: Get a good grade	Incorrect mapping: no repetitive action, no accumulation.	An original example. A series of actions, no accumulation. Correct mapping would be: Pay attention in one class; Level of understanding

Summary: 50 minutes into the workshop's first session, and only one student got it right. Most students had trouble inventing an example that has a repetitive action that leads to a direct accumulation. The common problems were:

- Making a story with a beginning action that is not repetitive (the natural tendency to use narrative causality), and mix the repetitive action with the delayed process.
- Use a "one-time effect" instead of an accumulation.
- Create a series of connected actions instead of one repetitive action with a delayed process.

3. **Student-made examples: Continuous Action leads to Accumulation**

Time occurred: Minute 66-84 in the first session

In this activity I handed out blank cards and instructed the students to invent their own examples, map their examples onto the FlowBlocks model, and present their examples to the group. The FlowBlocks model was: Continuous Inflow (the dial block) leads to one Straight block and then to an Accumulator block.

The students have to figure out on their own how many cards to create and how to map the different cards onto the FlowBlocks model.

The goal of this activity is to evaluate if the students create an Action card that is continuous and an Accumulation card that is directly affected by the action.

Students' Example Cards	Mapping Analysis	More details
Inflow: Drive to work; **Stock**: Total number of miles driven	Correct mapping	An original example. Continuous, repetitive action with direct accumulation.
Inflow: Riding a bike (pedaling) **Stock**: Total number of pedals you do	Correct mapping	An original example. Continuous, repetitive action with direct accumulation.
Inflow: Running several times a week; **Stock**: Accumulation of times you go running + your run time gets better	Almost correct mapping.	An original example. Accumulator represents two things: one increases with more of the action (number of time you go running), and one decreases with more of the action (your run time gets better).
Inflow: Speed of snow fall **Stock**: Accumulation of snow	Correct mapping	An original example. Continuous, repetitive action with direct accumulation.
Inflow: Cat is hungry **Stock**: Cat eats food	Incorrect mapping.	An original example. Cause and effect relationship with no accumulation.
Inflow: Weekly paycheck	Correct mapping.	Not an original example. Continuous, repetitive action with

Stock: Money accumulates with interests		direct accumulation.
Inflow: Sending an email; Number of emails sent; Number of emails received;	Incorrect mapping.	An original example. A repetitive action, but accumulation is represented at a step in the process with additional actions after. Correct mapping would be: sending an email; number of emails sent or received.
Stock: Number of emails deleted		
Inflow: Working	Correct mapping.	Not an original example. Continuous, repetitive action with direct accumulation (money accumulates in bank account).
Stock: Bank account		
Summary: 70 minutes into the workshop's first session, and most students (6 out of 8) understood the continuous action concept (Flow) and the accumulation concept (Stock). The 2 students that mapped incorrectly understood the continuous action concept (Flow), but did not have a clear understanding of the accumulation concept (stock).		

4. **Ready-made examples: Continuous-Inflow; Accumulation; Continuous-Outflow**

   Time occurred: Minute 88-101 in the first session

In this activity I handed out ready-made cards and instructed the students to map the example onto the FlowBlocks model, and present their examples to the group. The FlowBlocks model was: Continuous Inflow (the dial block) leads to one Straight block and then to an Accumulator block, and Accumulator block leads to another Straight block through the Outflow dial. This model is a key dynamic structure, encapsulating many concepts of Systems, such as: simultaneous flows, dynamic accumulation, rate-of-change, dynamic equilibrium, and more.

The students have three cards to map, and need to figure out on their own which one is the Inflow, Accumulation, and Outflow.

The goal of this activity is to evaluate if the students understand that Inflow increases the accumulation, outflow decreases the accumulation, and both Inflow and Outflow influence the Stock (Accumulator) at the same time, independently.

Each student received a different example to map.

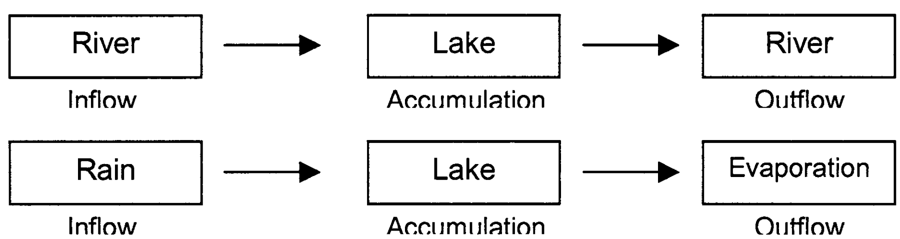
My Example Cards	Mapping Analysis	More details
Inflow: Walking on the rug; **Stock**: Dirt on rug; **Outflow**: Vacuuming the rug	Correct mapping	
Inflow: Rain **Stock**: Level of water in a lake; **Outflow**: Evaporation	Correct mapping	
Inflow: Things my family buys; **Stock**: Stuff at our house; **Outflow**: Garage sale	Correct mapping	
Inflow: Garbage collection from the city **Stock**: City's landfill; **Outflow**: Garbage decay	Correct mapping	
Inflow: People paying social security funds **Stock**: Amount of social security funds **Outflow**: People getting social security funds	Incorrect mapping: Inflow/Outflow mix.	This example involved unfamiliar terminology for teenagers, so the incorrect mapping might be due to misunderstanding of the terminology.
Inflow: Planting trees **Stock**: Forest area **Outflow**: New books printed	Correct mapping	
Inflow: Things that make me angry **Stock**: My Anger level **Outflow**: Things that calm me down	Correct mapping	
Inflow: Emission from cars & airplanes **Stock**: CO2 concentration in atmosphere **Outflow**: CO2 removal by oceans & trees	Correct mapping	
Summary: 100 minutes into the workshop's first session, and almost all students have mapped the example cards correctly, which shows that by now they have a good understanding of the difference between an Inflow and an Outflow, and understand the role of the Stock (accumulator).		

5. **Student-made examples: Continuous-Inflow; Accumulation; Continuous-Outflow**

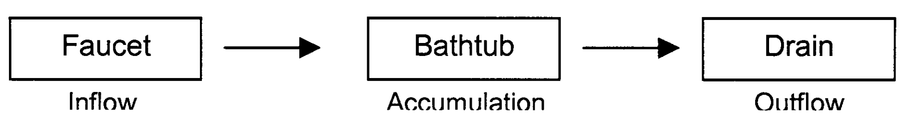
   Time occurred: 2nd session, minutes 6-17 into the session (one week after the first session)

In this activity I asked the students to write down in their journals a few examples for Inflow-Accumulation-Outflow models. I did not use the blocks as a model, but wanted to see if they can transfer the "model" concept to a written diagram. I then asked them to present their examples to the group just like in the previous activities.

This activity occurred at the beginning of the second session, one week after the first session. I started the second session with a short introduction of the Systems Thinking way of thinking, and to the Stocks & Flows diagramming language. I used a few examples we have modeled in the first session, such as:



I also used the classic bathtub example:



I asked the students to come up with two or more examples, and emphasized they should make an original example if possible, not one we have used or discussed in any of the sessions.

The goal of this activity was to evaluate if students understand simultaneous processes: Inflow and Outflow affecting the Accumulation simultaneously.

Student	Student's Examples	Mapping Analysis	More details
Female1	**Inflow**: Wind **Stock**: Leaves that have fallen **Outflow**: Leaves raked up	Correct mapping	An original example. A very dynamic one (the foliage is a very transient phenomenon).
Female1	**Inflow**: Amount of things bought at mall on credit card **Stock**: Amount of debt **Outflow**: Money paid off	Correct mapping	An original example. An excellent one, since the accumulation is a negative entity (debt).
Male1	**Inflow**: Waste **Stock**: Pollution **Outflow**: Recycle	Incorrect mapping: Inflow/Outflow mix.	An original example, but incorrect mapping. The outflow is defined as an additional cause that will reduce the accumulation, but it is reducing from the Inflow (Waste), before the Accumulation.
Male1	**Inflow**: People eating at a restaurant **Stock**: Makes more money **Outflow**: Pays employees	Correct Mapping	An original example.
Male2	**Inflow**: Rain **Stock**: Lake **Outflow**: Evaporation	Correct mapping	Not an original example.
Male2	**Inflow**: Money **Stock**: Bank account **Outflow**: Spending	Correct mapping	Not an original example.
Female2	**Inflow**: Cars coming in **Stock**: Number of cars in the garage **Outflow**: Cars going out	Correct mapping	Original example
Female2	**Inflow**: Rain **Stock**: Amount of lake H2O **Outflow**: Evaporation	Correct mapping	Not an original example.
Female2	**Inflow**: Meals sold **Stock**: Money made **Outflow**: Money for employees	Correct mapping	Original example
Female3	**Inflow**: Deposits **Stock**: Amount of $ in the bank **Outflow**: Withdraws	Correct mapping	Not an original example.
Female3	**Inflow**: Profits **Stock**: Money a company has **Outflow**: $ spent researching, developing, advertising	Correct mapping	Original example

Female3	**Inflow**: Number of minutes bought each month **Stock**: Total number of minutes **Outflow**: Number of minutes used.	Correct mapping	Not an original example.
Male3	**Inflow**: Tress cut down **Stock**: Timber used for building houses **Outflow**: Trees planted	Incorrect mapping: narrative causality	Original example, but incorrect mapping. "Trees cut down" is a good Inflow, but the rest is not causally-connected in the right way. One correct example would be: Trees cut down; Amount of timber for building houses; Building the houses.
	Inflow: Cars manufactured **Stock**: Cars bought **Outflow**: Cars sold	Incorrect mapping: narrative causality	Original example, but incorrect mapping. "cars manufactured" in a good inflow, but the rest is not causally-connected in the right way. One correct example would be: Cars manufactured; Cars available for retail; Cars sold/bought
	Inflow: Books bought **Stock**: How heavy your backpack is **Outflow**: How much HW you have in a night	Incorrect mapping: narrative causality	Original example, but incorrect mapping.
Female4	**Inflow**: Rain into lake **Stock**: Level of lake **Outflow**: River flowing out of lake	Correct mapping	Not an original example.
	Inflow: Fill up gas tank at pump **Stock**: Level of gas in the tank **Outflow**: Gas used by driving	Correct mapping	Original example
	Inflow: Minutes bought for a cell phone **Stock**: Number of minutes left on phone **Outflow**: Minutes used on phone calls	Correct mapping	Original example – a variation on the cell phone minutes used, but buying minutes as the inflow.
Male4	**Inflow**: Rain **Stock**: Lake **Outflow**: Evaporation	Correct mapping	Not an original example.
	Inflow: Eating **Stock**: Stomach **Outflow**: Using bathroom	Correct mapping	Original example
	Inflow: Buying **Stock**: Possessions **Outflow**: Selling	Correct mapping	Not an original example.

Male5	**Inflow**: Rain **Stock**: Lake **Outflow**: River going out	Correct mapping	Not an original example.
	Inflow: Money earned **Stock**: Money had **Outflow**: Money spent	Correct mapping	Not an original example.
	Inflow: Food eaten **Stock**: Energy stored **Outflow**: Energy used	Correct mapping	Original example
	Inflow: Stuff living **Stock**: Dead stuff **Outflow**: Stuff biodegrading	Correct mapping	Original example
Female5	**Inflow**: Deposit **Stock**: Money in bank account **Outflow**: Withdraw	Correct mapping	Not an original example.
	Inflow: Fill up tank at gas station **Stock**: Gas in tank **Outflow**: Drive	Correct mapping	Original example
	Inflow: Trees planted **Stock**: Amount of trees in forest **Outflow**: Trees cut down	Correct mapping	Not an original example.
Female6	**Inflow**: Births **Stock**: Bees in a hive **Outflow**: Deaths	Correct mapping	Original example
	Inflow: Sunlight + water **Stock**: # of flowers **Outflow**: Drought	Correct mapping	Original example
	Inflow: Seeds **Stock**: Trees **Outflow**: Drought	Correct mapping	Original example

Summary: 10 minutes into the second session (so 130 minutes from start of first session), and almost all students were able to create correct mappings, many of them original examples.

The numbers are:

Correct/Incorrect mappings: 27 out of 31 are correct mappings. The 4 incorrect mappings were made by two children; their errors can be identified as two types of misconceptions: tendency for narrative causality rather than simultaneous processes, and a tendency to relate to the Outflow as a cutback of the Inflow. I documented and defined these misconceptions in my Masters thesis (Zuckerman 2004, 2005).

Original/Not original examples: 19 out of 31 are original examples. The 12 non-original (examples that have been mentioned before) were all correctly mapped (obviously), and the two most popular ones were the Lake and the Money in the Bank examples. Some of the students made some variations to the used examples.

6. **Student-made examples: more advanced Inflow; Accumulation; Outflow**
Time occurred: 3rd session, minutes 1-10 into the session (six weeks after the second session)

In this activity I asked the students to write down on example cards new original examples for the Inflow-Accumulation-Outflow model.

This activity occurred at the beginning of the third session. For unpredictable logistical reasons the third session took place six weeks after the second session (instead of one week later as originally planned).

The goal of this activity is to evaluate if the students will come up with original examples that are correctly mapped, and maybe involving topics that are more relevant to their daily lives. In this set of examples I had no way to associate an example with a specific student, because they were written on blank example cards rather than the journal.

Student's Examples	**Mapping Analysis**	**More details**
Ice accumulated through global freeze period; Ice in Antarctica; Ice melted through global warming	Correct mapping	Original example. A global issue, very meaningful.
A person earns money; The amount of money the person has; The person spends money	Correct mapping	Not an original example. Probably not personally meaningful to the student daily life, but maybe it is.
It snows; Amount of snow on ground; The snow starts melting due to the sun's heat	Correct mapping	Not an original example. Was mentioned before by one of the students but not one of my ready-made examples.
Amount of rain fall; Amount of water in a lake; Amount of evaporation	Correct mapping	Not an original example.
Put food on the table; Amount of food on the table; Someone eats the food	Correct mapping	Original example, relevant to student's daily life.
Water poured into bottle; Amount of water in the bottle; Someone drinks the water OR leak in the bottle	Correct mapping	Original example, somewhat relevant to student's daily life.
Cars being parked;	Correct	Not an original example, was

Cars in a parking lot; Cars leaving	mapping	mentioned before by another student.
Write down words; Words accumulate; Eraser deletes words	Correct mapping	Original example; seems very reflective.
Buy new clothes; Accumulate more clothes; Donate older clothing	Correct mapping	Original example; is relevant to student's life.
Leaves fall from tree; leaves collect on ground beneath tree; leaves cover ground or you can decrease by raking	Incorrect mapping at first (narrative causality), Fixed Outflow when simulated to the group	Original example. During the simulation, the student changed the Outflow from "leaves cover ground" to "decrease by raking".
Good grades; Accumulation of good grades; Good term grade or GPA	Incorrect example: narrative causality.	Original example. But incorrect mapping. Inflow-Accumulation pair is fine, but the Outflow is just a next step.

Summary:

Out of 11 student-made examples, two were incorrect mappings, both with the "narrative causality" tendency. One student corrected her error while presenting her example to the group (simulating the example using FlowBlocks).

The range of examples varied. Five examples were not original ones, which is a relatively high percentage. Some of the reasons for that can be the long time that passed since the last session (6 weeks), so students might have forgotten this examples were mentioned before. The six original examples were grate, all of them are related to the student's daily lives (food on the table, drink water from bottle, write down words, buy & donate clothes, get good grades), and one is a global issue (ice melting/global warming).

Overall there are two conclusions:

- There is not a major change from the last Inflow-Accumulation-Outflow activity (activity 5). This means that for students that have not shaken-off their tendency for "narrative causality" would probably need more individual coaching & instruction in order to shake it off.
- With more FlowBlocks playtime and making-analogies activities the students were able to come up with more daily-life examples.

7. **Student-made examples: positive feedback (self reinforcing systems)**

Time occurred: 3rd session

In this activity I introduced the positive feedback concept and some examples. The way I introduced it was in the same way as the previous concepts - start with open-ended play session, move on to directed play, followed by mapping activity of ready-made cards, and presentation of the mapped examples to the group. After that, I asked the students to create their own examples by mapping cards onto the FlowBlocks "self reinforcing" model.

This activity occurred at the beginning of the third session. The goal of this activity is to evaluate if the students will come up with original examples that are correctly mapped, and maybe involving topics that are more relevant to their daily lives. In this set of examples I had no way to associate an example with a specific student, because they were written on blank example cards rather than the journal.

Student's Examples	**Mapping Analysis**	**More details**
Someone buying clothes from a store; Number of people who go to that store; people see others wearing the clothes, advertising, and other stuff so more go there;	Correct mapping	Original example. "Social Epidemic" class.
Kids go to a pizza place after school; Number of kids accumulate that go to a pizza place; Those kids tell other kids how fun it is so they go, as well as the new kids.	Correct mapping	Original example. "Social Epidemic" class.
Someone shops at a 'cool" store for clothes. They wear a cute shirt to school; Lots of people comment that they like the shirt. The person with the shirt gets a boyfriend/girlfriend; More people shop at that store.	Correct mapping	Original example. "Social Epidemic" class.
Something is fashionable; Number of people wearing the fashion; Influence of being fashionable, popular, fitting in.	Correct mapping	Original example. "Social Epidemic" class. A more general example. Defining the "Fashion Fad" class of phenomenon.
Someone gets a good education at a school; Influence: word-of-mouth, people hear about the school; Number of people applying to that	Correct mapping	Original example. "Social Epidemic" class.

school.		
Amount of people eating a new ice cream flavor; People telling other people about new flavor; People buying the new flavor.	Correct mapping	Original example. "Social Epidemic" class.

Summary:

Positive feedback or "reinforcing loop" is an important and hard-to-learn concept. This activity showed that after an experience of several hours using FlowBlocks for non-feedback models, the introduction of feedback model was well accepted and the students gained a good intuitive understanding of the concept in a relatively short time (20-30 minutes). All of the examples were correctly mapped, and all of the examples were original examples. This also strengthened the assumption from the previous activity about the Used vs. original examples, that because of the long break between session two and three the student might have forgotten which examples have been mentioned before.

This activity also surfaced a limitation that should be addressed. It is easy to notice that all examples belong to the same "class" of phenomenon, the "social epidemic" or "word-of-mouth" self-reinforcing phenomenon. There are many other classes of relevant examples, such as virus-spreading or interest-rate bearing, but the students have strongly preferred the social ones. This limitation can be easily addressed by verifying that the ready-made examples given to the students represent a good variety of the different classes of positive feedback phenomenon (social, medical, economics, physics etc.)

8. **Student-made examples: negative feedback (self regulating systems)**
   Time occurred: 3rd session

In this activity I introduced the negative feedback concept and some examples. The way I introduced it was in the same way as the previous concepts, start with open-ended play time, move on to directed play, followed by a ready-made examples-mapping with presentation to the group. After than, I asked the students to create their own examples by mapping cards onto the FlowBlocks "self regulating" model.

This activity occurred towards the end of the third session. The goal of this activity is to evaluate if the students will come up with original examples that are correctly mapped, and maybe involving topics that are more relevant to their daily lives. In this set of examples I had no way to associate an example with a specific student, because they were written on blank example cards rather than the journal.

Student's Examples	**Mapping Analysis**	**More details**
The amount of people in a city; People moving in/people moving away; People deciding to move or stay.	Correct mapping	Original example. Amount of people in a city regulates itself. If many people leave, then later less people would leave because the city becomes less crowded/more opportunities etc.
People in a crowded room; More people in the room everyone leaves quickly and the rate of people leaving is high. Eventually there are a few people in the room, people leave slowly and the rate of people leaving is slow.	Correct mapping	Original example.
Amount recycled; Wearing down of material cause of recycling; Material too old to be recycled.	Correct mapping	Original example. The more times a material is recycled, the less it can be continued to be recycled.
Species reproducing; Number of species in an area; Species migrating to the area.	Correct mapping	Original example. The more crowded a resource is, the less there is from that resource, and new species will look for alternatives.
Amount of insects; Number of insects dying; Pesticides applied.	Correct mapping	Original example. The more insects, the more effective the pesticide will be. But with less insects, it will be "harder" for the pesticide to harm them (they are more spaced around, easier "hiding" spots, etc.).
If there is a low of rainfall; the rain accumulates on the lake; level rises above the max + overflows.	Correct mapping	Original example. The self regulating concept of "overflow" in a lake or any water liquid "container".
Accumulation of height/body size; old body grows the less it grew.	Correct mapping	Original example. A natural phenomenon

		The "limits to growth" in living systems.

Summary: negative feedback, also called "balancing loop" or "self regulating" system, is one of the harder concepts in Systems Thinking. I assume that the previous hours of hands-on experience with FlowBlocks making simpler models have "paved the road" for easier learning of the more advanced concepts. In this case, all seven examples were original examples and all correctly mapped. The examples varied in their type, and are all very advanced from the topic and concepts involved.

CHAPTER 7. CONTRIBUTION

In the Flowness + FlowBlocks research project I presented contributions on several levels.

I have shown that middle school aged students, with no prior instruction in Systems Thinking, can successfully map & invent their own daily life examples using FlowBlocks models as a learning aid, involving systems concepts such as Flows, Stocks, Positive Feedback, and Negative Feedback. I have shown the trajectory in which students' understanding progresses, starting with surface-level focus, and gradually shifting towards behavior-level focus, reasoning and reflecting about the causality and dynamics of everyday life.

I have accomplished that by introducing the students to FlowBlocks, asking them to play; make models; map, create, and share their daily life analogies in a collaborative workshop setting. The FlowBlocks unique design and workshop method provides a unique opportunity for learning, making Systems concepts visible and accessible, and promoting analogy-making and reflective conversation among the workshop participants.

FlowBlocks unique design has been inspired by the great Learning Objects designers of the 19th and 20th centuries: Friedrich Froebel & Maria Montessori. I have uncovered the design principles behind Froebel's & Montessori's brilliant designs, in an effort to inform and inspire contemporary designers of interactive learning technologies.

I have traced back the influences on Froebel and Montessori, showing how each of them belongs to a different school of thought. I have defined a new classification for educational toys and Learning Objects: the Froebel-inspired "Construction & Design" category and the Montessori-inspired "Conceptual Manipulation" category. I showed that this classification is valid also for contemporary toys across different domains, including the static; dynamic; and computational toys domains.

I have implemented FlowBlocks as a unique blend between "Conceptual Manipulation" and "Construction & Design" - a mix of an open-ended construction kit and conceptual puzzle, that proves to be highly engaging for children in spite of (and maybe due to) its lack of familiar visual analogies.

I have designed the Flowness modeling language, the underlying language behind FlowBlocks, based on existing Systems Dynamics languages. Flowness is the first Systems Thinking language that is intuitive for novices AND computationally simulate-able. Today, Systems Thinking teachers & trainers have no tool that can allow children or novices to create their own models. Their only choice is to use diagramming tools or ready-made Systems Dynamics simulations that allow limited interaction only.

The Flowness + FlowBlocks research project does not end here. The SEED foundation has agreed to sponsor the manufacturing of many FlowBlocks sets for distribution in their SEED-sponsored schools located in developing countries around the world. With a mass-production version of FlowBlocks the outreach and research potential will greatly increase. On the research side, it will enable researchers from the Learning Sciences and Systems Thinking communities to conduct in-classrooms studies, to better understand the range of learning FlowBlocks promotes. On the outreach side, it will spread the language and vision of Systems Thinking, and will help teachers appreciate their students' creative thinking.

CHAPTER 8. CONCLUSION

Three Issues for The Future of Systems Thinking

The field of System Dynamics was created during the mid-1950s by Professor Jay W. Forrester at MIT as a management discipline, in an effort to inform businesses about the root cause for the dynamic complexities they experience. The main modeling language of System Dynamics is Stocks and Flows modeling, which is usually done by expert modelers and is not accessible to novices.

Systems Thinking is a more accessible version of System Dynamics, promoted by veteran System Dynamicists in an effort to reach a larger and more diverse audience. Systems Thinking has reached a larger audience than System Dynamics, especially among educators and management consultants, but has not reached a wide spread recognition. The main tools of Systems Thinking are Casual Loops Diagrams - a powerful diagramming convention, and the Systems Archetypes – a specific set of Causal Loops Diagrams that present common patterns experienced in organizations.

Efforts to promote Systems Thinking are a step in the right direction, and have achieved some success, but new approaches are needed to reach a larger and more diverse audience. I believe that understanding Systems concepts is critical for the future of our planet and societies, and dedicated my PhD research to making System Dynamics and Systems Thinking concepts more accessible to novices.

The following are three issues that might help Systems Thinking reach a larger and more diverse audience:

1. Flagship example
2. Technology
3. Dissemination

1. **Flagship example:** why bathtub is not the right one

The most common example in the field is the bathtub example. I argue that the bathtub example is not a good choice to represent the field. The bathtub example has some advantages, it's a concrete representation of a stock, has continuous inflow and outflow, and describes a very familiar situation. But, it has major disadvantages. People's everyday experience with a bathtub is a sequential one: (1) first one opens the faucet for water to fill in the tub (2) the tub is being filled with water (while the drain is closed) until the desired water level is reached and the faucet is shut off. The water stay in the tub for quite some time, in a static state (3) one opens the drain only after a while, releasing all the water from the bathtub.

This is a sequential process rather than a simultaneous one. Rarely people experience a bathtub in a dynamic state of water flowing in and out at the same time. Simultaneous processes vs. sequential processes are one of the core concepts of Systems Thinking. In my research I clearly saw a tendency among children to prefer sequential processes over simultaneous processes. The "flagship example" should promote simultaneous thinking rather than sequential one.

One possible example can be a lake. A lake appears to be static, but never is. There are always simultaneous processes of Inflows and Outflows: incoming river, rain, and underwater are the Inflows; outgoing river and evaporation are the outflows. A lake is familiar enough for most people, and is part of important natural and human systems, so the example can be easily extended to unfold local and global interactions and interdependencies between natural and human systems.

Continuing to use the bathtub example will reinforce people's natural tendency for sequential processes.

2. **Technology:** a new modeling and simulation environment

There are two common modeling languages for Systems Thinking.

> The Stocks and Flows modeling language can be simulated using Vensim and Stella, visual modeling and simulation software tools. These environments are

powerful for expert modelers, but present many barriers for novice modelers. Specifically, it is extremely hard to explore Systems concepts by tinkering with the tools without the appropriate training.

The Causal Loops Diagrams modeling language is a powerful diagramming convention that is easy-to-learn, but unfortunately can not be simulated.

A new modeling language and simulation environment must be created, one that is easy-to-learn, represents the core Systems Thinking concepts, and can be simulated. More specifically, the new simulation environment should enable children and novices to learn Systems concept by exploring and tinkering, without any formal training.

I have created such a language - the Flowness modeling language. In my dissertation I have presented the Flowness elements and models, including a set of Universal Models that gradually progress from easy models to more advanced ones.

I have also created a simulation environment for Flowness. My simulation environment is tangible – a physical set of blocks with embedded computation I call FlowBlocks. In my dissertation I have showed that FlowBlocks allows middle-school children to learn core Systems concept by exploring and tinkering, without any formal instruction. FlowBlocks tangibility has great advantages for learning in co-located small groups, but serious limitations in distribution and cost due to its physical nature.

A new software simulation environment should be created for Systems Thinking, based on an easy-to-learn modeling language, and enabling learning by exploration and tinkering. There are many ways to design a modeling language. Flowness is one example for an easy-to-learn simulateable language, but there can and should be other approaches.

3. **Dissemination:** an online community of simulations

Today, there is no clear way for Systems Thinkers to spread the vision of Systems Thinking. Moreover, there is an ongoing criticism by System Dynamicists that Systems Thinking is "too soft", does not incorporate modeling & simulation, and does not help

people learn core systems concepts. The Systems community today is focused at two extremes: too simple models or too complex ones. A new Systems Thinking simulation environment can change this, serving as a bridge between the two Systems communities (System Dynamics and Systems Thinking).
The new software simulation environment should be implemented as an "online community of simulation", in the spirit of web 2.0 services that enable Internet users worldwide to create and share through an easy-to-use online interface.

Setting up an online community of easy-to-create Systems simulations could serve as a hub in which existing Systems Thinkers world wide could contribute their Systems knowledge with little effort, making it much easier for novices around the world to experience and learn about Systems Thinking concept.

CHAPTER 9. REFERENCES

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